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Established in 1818 by Benjamin Silliman

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American Journal of Science

SEPTEMBER 1952

ONE HUNDRED AND FIFTY YEARS OF GEOLOGY AT YALE

M. L. JENSEN

ON September 9, 1802, Benjamin Silliman was appointed to the Professorship of Chemistry and Natural History in Yale College at New Haven, Connecticut. This marked the advent of a Department of Earth Science and it seems fitting, therefore, that we should recall this academic birth of Geology in America now, a century and a half later.

At the time Silliman received his appointment he was but 23 years of age but he was a graduate of Yale College and had been admitted to the practice of law in the State of Connecticut. He had not been trained in chemistry or natural history but he spent the following four years in preparing himself to teach the subjects of chemistry, mineralogy, and geology. He also began collecting specimens to be used in the mineralogy course, and he attended the lectures on chemistry by James Woodhouse and Benjamin S. Barton in Philadelphia during the two winters immediately following his appointment. He visited Europe and in the words of his son-in-law, J. D. Dana, in "the mines, quarries, and cliffs of England, the crags of Scotland, and the meadows of Holland, he looked for knowledge, and from these and the teachings of Murray, Jameson, Hall, Hope, and Playfair, at Edinburgh, Professor Silliman returned, equipped for duty,—albeit a great duty, —that of laying the foundations and creating almost out of nothing a department not before recognized in any institution in America" (Gilman, p. 160).

Silliman began the collection of minerals and rocks by sending a "half bushel of unlabeled stones" to Philadelphia to be named.

In 1810, through the influence of Silliman, Col. George Gibbs of Newport, R. I., offered to deposit at Yale his rich

and extensive collection of minerals, which he had obtained in Europe. Fifteen years later, this collection was purchased at a cost of $20,000 and became the property of Yale College. This entire sum was raised through individual donations by citizens of Connecticut and other eastern states. This formed the nucleus of the mineralogical collection which Yale now has. In contrast to the "half bushel of unlabeled stones," Yale recently received on loan the Carl Bosch Mineralogical Collection, the shipping of which to New Haven required the use of 2½ railroad cars.

It was through the arguments of Col. Gibbs that Silliman (1834) undertook the task of providing a scientific journal for the naturalists of America. The first number was published in 1818 and contained the following title:

THE
AMERICAN
JOURNAL OF SCIENCE
MORE ESPECIALLY OF
MINERALOGY, GEOLOGY,
AND THE
OTHER BRANCHES OF NATURAL HISTORY,
INCLUDING ALSO
ARCHITECTURE
AND THE
ORNAMENTAL AS WELL AS USEFUL
ARTS

CONDUCTED BY
BENJAMIN SILLIMAN

In contrast, the present policy of the editors of the Journal is to limit the subject matter of papers to topics pertaining essentially to geology.

The Journal, more popularly known as Silliman's Journal, was a success from the beginning in all respects except for the "pecuniary" aspect. The editorial preface of vol. III (Silliman, 1820) states that "we are now bound in justice to the interest of American Science, not to withhold from its patrons, the fact that the two first volumes of this Journal have been thus far, in a pecuniary way, losing concerns." The same volume also contains the note that "the editor is compelled to postpone many miscellaneous articles which were in readiness." Silliman realized, quite obviously, the great need

of his Journal as a scientific periodical and he therefore provided "pecuniary" support from his own pocket. No wonder it was called "Silliman's Journal."

The preface of vol. V (Silliman, 1822) states that "a trial of four years has decided the point, the American Public will support this Journal. Its pecuniary patronage is now such, that although not a lucrative, it is no longer a hazardous enterprise."

Economic difficulties did not dampen Silliman's philosophical attitude. In one of his earliest papers (Silliman, 1818, p. 230) he comments, "How happy is it, that the poison of the rattlesnake, is not conjoined with the size of the Boa-constrictor, and with the speed of the antelope." It does seem, however, that he had characteristics of the forgetful professor. In a note "to correspondents," Silliman (1821) confesses that "some memoranda of errata forwarded to us have been mislaid; they are, however, either obvious or unimportant.—(Editor)."

Schuchert (1918, p. 51) has described Silliman as "the first [in America] to take up actively the teaching of mineralogy and geology based on collections of specimens. He spread the knowledge in popular lectures throughout the Eastern States, graduated many a student in the sciences, making of some of them professional teachers and geologists, provided all with a journal wherein they could publish their research, organized the first geological society, and through his students, the first official geological surveys, and by his kind words and acts, fostered, and held together American scientific men for fifty years."

It might be added that he fostered four sons and five daughters, five of whom were of great aid in continuing his high hopes and ideals of science (three sons and one daughter died in infancy). His son, Benjamin Silliman, Jr., became Professor of Chemistry at Yale College and second editor of the American Journal of Science. This son should receive an important share of the credit for initiating the petroleum industry. The results of a chemical study upon the various properties of a fractionated sample of Pennsylvania crude oil, collected from a seep, were described in a "Report on the Rock Oil, or Petroleum, from Venango Co., Penn. with special reference to its use for illuminating and other purposes," which was written by Benjamin Silliman, Jr., and dated April

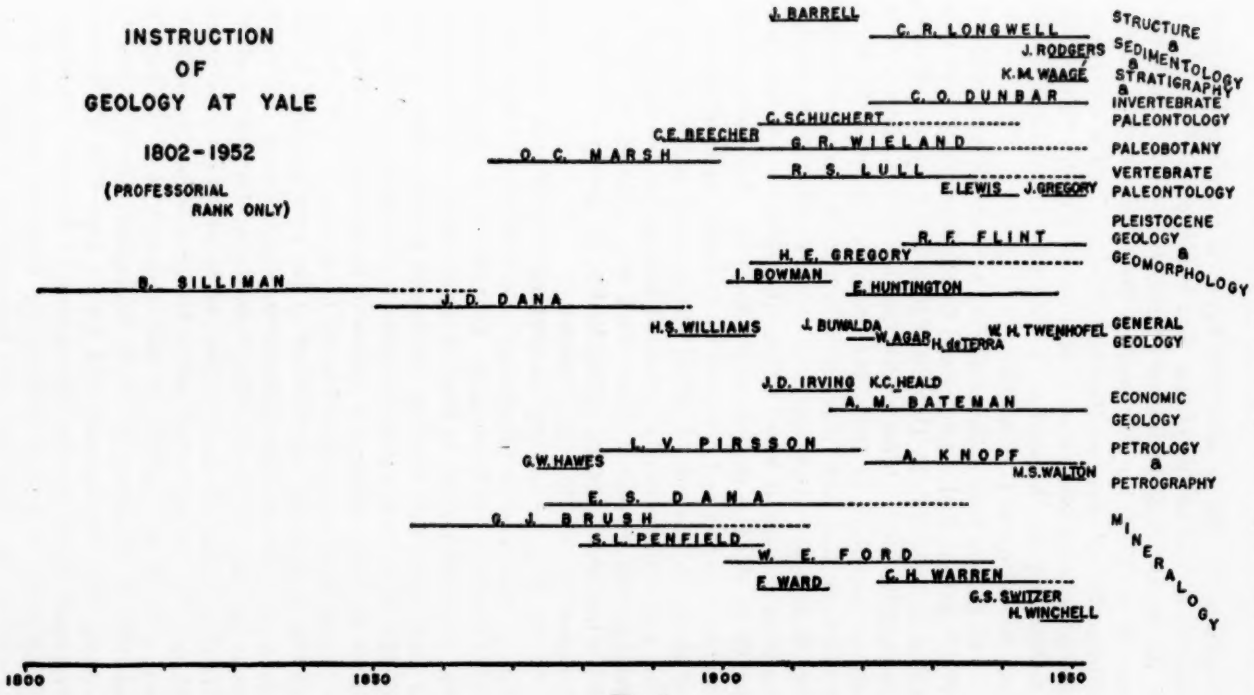
16, 1855. In the conclusion of the report, he stated, "gentlemen, it appears to me that there is much ground for encouragement in the belief that your Company have in their possession a raw material from which, by simple and not expensive process, they may manufacture very valuable products."

In the words of Bateman (1950, p. 652), "Casual discussion of [Silliman's] discovery with three of his friends led to forming a small company to drill for oil, just as was done for salt. One member supplied a young temporary conductor from his railroad, who was sent to Oil Creek, Pennsylvania. To give him dignity in the community they bestowed upon him the title of Colonel by addressing letters in advance of his arrival to Col. E. L. Drake." It is now, of course, common knowledge that "Colonel" Drake's well struck oil at a depth of 69 feet and became the first producing oil well.

Two of Silliman's most promising students became his sons-in-law. One, O. P. Hubbard, became Professor of Chemistry at Dartmouth College whereas the second, James Dwight Dana, who married Henrietta Frances Silliman, remained at Yale. Soon after their marriage, Dana received overtures from Harvard University, through Asa Gray, to join the distinguished group at Cambridge. He, however, accepted the newly created chair of Silliman Professorship of Natural History at Yale, presumably to the great delight of his wife, her family, especially her father who wished to retire, and his New Haven friends. Actually, the chair was made possible through the financial aid provided by Professor Edward Salisbury. Dana's son, Edward Salisbury Dana, named after this kind benefactor, became Curator of Mineralogy in the year 1874 and was Professor and Professor Emeritus until 1935.

It would require a voluminous work to treat adequately and trace fully the genealogy of instruction in geology at Yale. Figure 1 may suffice, however, to indicate schematically the general evolution and specialization of geologic instruction at Yale. The abscissa of the diagram is a plot of time for one and one-half centuries; the ordinate represents roughly the specialized fields that have developed during that time within the broad scope of geology.

The description and composition of rocks and minerals formed the foundation of geology and it is, therefore, not surprising that the field of mineralogy has received great


INSTRUCTION
OF
GEOLOGY AT YALE
1802-1952
(PROFESSORIAL
RANK ONLY)
B. SILLIMAN
J. D. DANA
H. S. WILLIAMS
J. BARRELL
C. R. LONGWELL
J. RODGERS
K. M. WAAGE
STRUCTURE
SEDIMENTOLOGY
&
STRATIGRAPHY
C. O. DUNBAR
C. SCHUCHERT
C. E. BEECHER
G. R. WIELAND
INVERTEBRATE
PALEONTOLOGY
O. C. MARSH
PALEOBOTANY
R. S. LULL
E. LEWIS
J. GREGORY
VERTEBRATE
PALEONTOLOGY
R. F. FLINT
PLEISTOCENE
GEOLOGY
&
GEOMORPHOLOGY
H. E. GREGORY
I. BOWMAN
E. HUNTINGTON
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ECONOMIC
GEOLOGY
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PETROLOGY
&
PETROGRAPHY
E. S. DANA
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S. L. PENFIELD
W. E. FORD
F. WARD
C. H. WARREN
G. S. SWITZER
H. WINCHELL
MINERALOGY
1800
1850
1900
1950

Fig. 1

emphasis. As can be seen from figure 1, there has been some overlap of instruction in this field in the past.

As an aid in identification of minerals, G. J. Brush presented, in 1874, his "Manual of Determinative Mineralogy with an Introduction on Blowpipe Analysis." (The determinative tables were based upon Professor von Kobell's "Tafeln zur Bestimmung der Mineralien.") The text was later enlarged and revised by S. L. Penfield.

The Danas, both father and son, were active mineralogists. The "System of Mineralogy and Crystallography," first published in 1837 (J. D. Dana was then but 24 years of age), reached the sixth edition before the turn of the century. This edition, published in 1892, was "entirely rewritten" by E. S. Dana with some aid from his father. J. D. Dana's "Manual of Mineralogy" first appeared in 1848 and went through fourteen editions at Yale. A fifteenth edition was contemplated by W. E. Ford at the time of his death in 1939, and was later "entirely revised and rewritten by Cornelius S. Hurlbut, Jr.," of Harvard University in 1941. The sixteenth edition appeared this year. The mineralogy group at Harvard is now completely revising the "System." This work was initiated by W. E. Ford but because of his failing health, the group at Harvard relieved him of this extra burden.

C. H. Warren received his doctoral degree from Yale and became Professor of Mineralogy and Petrology at Massachusetts Institute of Technology. In 1922 he returned to Yale to accept the position of Dean of the Sheffield Scientific School, a position he held until his retirement in 1945. During much of this time, he remained in contact with undergraduate students through teaching a course in megascopic petrology.

G. W. Hawes is referred to by his successor, L. V. Pirsson (1918, p. 228) as "the earliest of the petrographers in this country." Pirsson himself, however, was certainly one of the early investigators in this field, even though his undergraduate training at Yale was in chemistry and he served as an analytical chemist for several years after his graduation. In 1889 he was offered the position of field assistant to J. P. Iddings and W. H. Weed of the U. S. Geological Survey. Upon his return from the summer field season (spent in Yellowstone National Park) he was determined to become a geologist. Incidentally he was an enthusiastic fisherman and the trout streams of the West may have influenced his decision.

In 1893 Pirsson began teaching physical geology. This led to the publication, in 1915, of the first Yale Physical Geology and Historical Geology textbooks, Schuchert being author of the Historical Geology volume.

Pirsson retained, however, his specialty of petrology and was a member of the famed C.I.P.W. (Cross, Iddings, Pirsson, Washington) group. According to Cross, Pirsson was recognized as the "moderator" during lively sessions of these four petrologic authorities.

Adolph Knopf undertook the duties of Professor of Petrology at Yale in 1920 and was the latest professor to retire from the department. Upon his retirement, the respect and admiration for this man by Yale geology students and over 300 of his former students was such that they presented a commemorative plaque, now on display outside his former office, bearing his profile and the following inscription: "Adolph Knopf, Inspiring Teacher, Scholar, Friend. Presented by his students of 1920-1951."

J. D. Irving, although specially trained in petrography, entered the allied specialty of economic geology and surely seemed destined for fame in the field of mineral dposits when he died in France, at the youthful age of 44, while serving with the A. E. F. He was succeeded by a former student, who has now been teaching economic geology at Yale for over thirty-five years, Professor Alan M. Bateman.

Organic geology[1] became a recognized specialty at Yale in the year 1866 with the appointment of O. C. Marsh as Professor of Paleontology. Professor Marsh received his B.A. and M.A. degrees at Yale and performed his doctoral requirements at Heidelberg. Fortunately for Yale, Marsh was not only an able but also a rather persuasive man and the nephew of Mr. George Peabody. On November 1, 1866, Yale gratefully accepted a gift from this benefactor for the establishment of a Museum of Natural History, and ten years later the first Peabody Museum of Natural History at Yale was completed.

R. S. Lull taught vertebrate paleontology for thirty years and became Professor Emeritus in 1936. He is, however, still an active man and he can often be found at work in the Peabody Museum.

[1] Although the phrase "organic geology" seems rather unusual, it is of interest to note that L. V. Pirsson occupied the position of Professor of Inorganic Geology while instructing in petrology, petrography, and physical geology.

C. E. Beecher taught invertebrate paleontology and stratigraphy until his death in 1904, when he was succeeded by Charles Schuchert. Schuchert had left school at the age of fourteen and had entered his father's furniture business only to see the establishment destroyed twice by fire. The collecting of fossils had been his hobby from the time he was eleven years of age, with the result that he became a recognized authority on brachiopods, even though he began as an amateur paleontologist and never attended a college lecture until he gave his first lecture at Yale at the age of 46! His attempts to organize and improve the instruction of stratigraphy led him to adopt a method of plotting the location and thickness of stratigraphic sections on base maps. This led to his great interest in paleogeographic maps and made him the world's recognized leader in paleogeography. His portrait, presented to him by his former students when he became an octogenarian, hangs alongside that of O. C. Marsh in the Peabody Museum (Dunbar, 1942).

Schuchert's successor was his protegé and former student, C. O. Dunbar, who is now the Director of the Peabody Museum of Natural History.

G. R. Wieland has been at Yale for over fifty-five years where he has acquired a worldwide reputation as a paleobotanist. When the King (then Crown Prince) of Sweden visited New Haven in 1926, he spent almost all of his time with Wieland discussing the latter's fine collection of cycadeoids, much to the disappointment of the Welcoming Committee.

Although Joseph Barrell occupied the position of first Professor of Structural Geology at Yale, the subject of this field had received previous recognition. In fact, Barrell (1918, p. 152) himself has referred to the description of an overturned fold submitted to Silliman and his Journal by J. H. Steele, in 1825, and Barrell noted that as far as he "is aware this is the first recognition in geological literature of the evidence of a horizontally compressive and overturning force as a cause of folding."

Barrell was a great believer in the importance of knowledge gained from a study of the history of ideas pertaining to a subject (which incidentally is an excuse for writing a paper of this type), for he has said (1918, p. 134), "Those interested in any branch of science should, as a matter of education,

read the history of that special subject. A knowledge of the stages by which the present development has been attained is essential to give a proper perspective to the literature of each period. Much of the existing terminology is an inheritance from the first attempts at nomenclature, or may rest upon theories long discarded. Popular notions at variance with advanced teaching are often the forgotten inheritance of a past generation."

Joseph Barrell was one of three professors of geology at Yale who died during the 1918-19 academic year, the other two being L. V. Pirsson and J. D. Irving. C. R. Longwell returned from France in 1919, completed his doctoral requirements and began teaching structural geology at Yale in 1920.

H. E. Gregory received his Ph.D. from Yale and began teaching courses in geography and physiography at the turn of the century. He was immensely interested in the geology of the Colorado Plateau where he spent many field seasons. Isaiah Bowman and Ellsworth Huntington represented geography while that subject was allied with geology in one department at Yale.

In 1925, R. F. Flint entered the department, and he has since stressed the great importance of Pleistocene geology, espcially the stratigraphic aspects of this field. The C^{14} isotope has become a further tool in this field and the Geochronometric Laboratory at Yale has been set up for the purpose of determining the age of suitable specimens which are known to be accurately placed stratigraphically.

H. S. Williams, the originator of the Sigma Xi Society, taught a general historical geology course until 1904 at which time he returned to Ithaca, New York, and accepted the position of head of the department of geology at Cornell University. Several men have conducted the introductory general geology course but only those of professorial rank are included in figure 1. A number of those there listed in special fields have given important parts of their time to the teaching of general geology.

At the conclusion of World War II, the Department of Geology at Yale consisted of five full professors. Within a year, considerable young blood was infused with the additions of J. T. Gregory, John Rodgers, K. M. Waagé, and Horace Winchell. A few years later, M. S. Walton also entered the fold.

Many a professor has remarked during a moment of exasperation that teaching would be wonderful if it were not for the students. It is, however, needless to say that Yale is proud of her geologic graduates and the successes they have achieved. A complete record of the number of undergraduate degrees awarded in geology at Yale is unavailable. Figure 2, however, is a graphical representation of the number of graduate degrees awarded during the past. It is obvious from the graph that the number has been gradually increasing. The first Ph.D. in geology, and the tenth Ph.D. given by Yale[2] was awarded to William North Rice in the year 1867. His dissertation was entitled, "The Darwinian theory of the origin of species." In 1950, seven master's degrees and ten doctor's degrees were awarded in the field of geology.

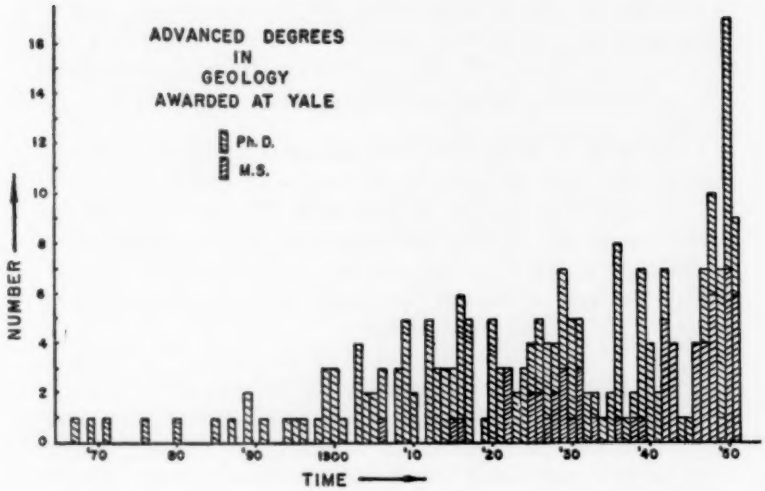

Fig. 2

[2]Yale was the first institution in America to award the degree of Doctor of Philosophy.

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STRATIGRAPHY OF THE DUNDAS HARBOUR AREA, DEVON ISLAND, ARCTIC ARCHIPELAGO

V. E. KURTZ, A. H. McNAIR and D. B. WALES

ABSTRACT. Cambrian and Ordovician sediments at least 3,660 feet thick overlie Precambrian gneisses along the southeastern shore of Devon Island. The rocks have a very gentle northwest dip and are broken by a few minor north and northwest trending high-angle normal faults.

Six new formations are described. They range from Lower Cambrian to Middle or possibly early Upper Ordovician in age. The longest hiatus in the stratigraphic sequence is represented by the absence of Upper Cambrian strata. Numerous intraformational conglomerates are present in both Cambrian and Lower Ordovician rocks. A thin bed of gypsum occurs in the Middle Cambrian.

The faunas at Dundas Harbour show many similarities to the Cambro-Ordovician rocks of the Kane Basin which lies between West Greenland and central Ellesmere Island. Stratigraphic and faunal evidence suggests that the marine transgressions of both the Lower Cambrian and the Lower Ordovician spreading from the Franklinian geosyncline reached Kane Basin earlier than they did the Dundas Harbour area.

INTRODUCTION

THE discovery of Middle Cambrian fossils on the west shore of Dundas Harbour in 1948 by D. B. Wales and R. P. Nickelsen indicated that a relatively thick stratigraphic section of Lower Paleozoic sediments could be studied at that place (Wales, 1949, p. 330). A grant-in-aid to McNair from the Arctic Institute of North America with funds furnished by the United States Government permitted Wales and Kurtz to spend twelve days in the Dundas Harbour area during the summer of 1949. The present paper summarizes the geological results obtained during the field work in 1949. A report is in preparation by Kurtz on the Cambrian and Ordovician trilobites and brachiopods collected from the Dundas Harbour area.

Aid to the field party was generously given by many persons. We are particularly indebted to Captain B. N. Rittenhouse, USN, and other officers and men of the *USS Edisto;* to the late Charles J. Hubbard, Chief of the Arctic Section of the U. S. Weather Bureau; to Dr. A. L. Washburn, Director of the Arctic Institute of North America; and to the members of the Royal Canadian Mounted Police stationed at Dundas Harbour.

Dundas Harbour (Lat. 74° 45′ N., Long. 82° 30′ W.) is located on the southeast coast of Devon Island, Northwest Ter-

ritories, in the Eastern Arctic (fig. 1). No previous stratigraphic investigation had been made along the southeast coast of the island. The nearest place in which any comprehensive work had been done is southeastern Ellesmere Island, where Schei measured sections of Paleozoic rocks during the second Norwegian Arctic expedition of the *Fram* in 1898-1902. The stratigraphic and paleontologic results of the *Fram* expedition have been presented by Holtedahl (1913, 1914, 1917), Loewe (1913), Meyer (1913), and Schei and Holtedahl (1926). In 1941 Bentham described the geologic structures and glaciers of southern Ellesmere Island. Scattered geological observations have been made on Devon Island by McClintock (1859) of the Cape Warrender area on the east coast; by H. Woodward (1878) of the Silurian fossils from Beechey Island, a peninsula forming the southwest coast of the island; and on raised marine beaches by Nichols (1936). The nearest area in the Arctic Archipelago in which comprehensive stratigraphic and paleontologic work has been done is Kane Basin on the central east coast of Ellesmere Island and northwest Greenland. In this area Poulsen (1946) and Troelsen (1950) reported on the Cambrian and Ordovician rocks and their fossils.

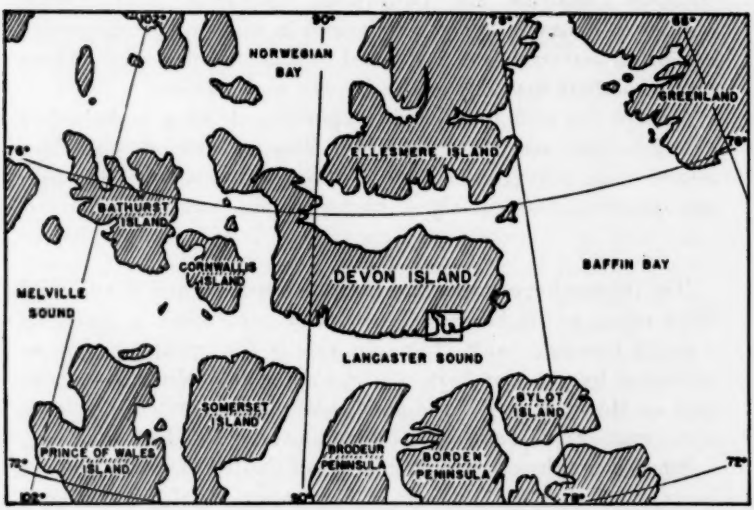


Fig. 1. Index map, showing location of the Dundas Harbour area.

PHYSICAL GEOLOGY

Dundas Harbour, approximately five miles long and one mile wide, occupies an abandoned north trending glacial valley (fig. 2). The western shore is bordered by steep cliffs, approximately 1700 feet high, consisting of Precambrian gneisses unconformably overlain by Cambrian and Ordovician sediments. The southern part of the eastern shore of the harbor is a low-lying peninsula extending to Nadlo and Walrus Point and consisting of Precambrian gneisses overlain by glacial deposits. The northern part of the shore is bordered by steep talus slopes and cliffs which range up to 1700 feet in elevation. The head of the harbor is formed by a broad outwash plain, four and one half miles long and approximately one and one half miles wide, that terminates at three ice tongues of the Devon Island ice cap.

The southern shore of the island west of Dundas Harbour is bordered by a strip of low lying ground one and one half to two miles wide covered by mantle and containing a conspicuous set of raised beaches.

The ice-free part of the island north of the coastal strip between Dundas Harbour and Croker Bay consists of a relatively flat erosion surface that truncates the gently northwest dipping Cambrian and Ordovician sediments. Both stream and glacial carved valleys are incised in this surface. Glacially deposited materials are restricted to abandoned glacial valleys and immediate margins of the ice cap and glaciers.

Except for cliff faces, rock exposures showing undisturbed relationships are not abundant. Frost-shattered outcrops, active stone polygons and stone stripes are common throughout the area, particularly in places having gentle slopes.

FAULTING

The depression occupied by Dundas Harbour and the alluvial filled valley at its head is structurally controlled, in part, by a north trending fault. The east side is the upthrown side as indicated by the elevation of the Cambrian-Precambrian contact on the east side of the valley. Maximum vertical displacement appears to have been approximately 400 feet.

Smaller northwest trending faults of limited displacement occur west of Dundas Harbour. The conspicuous structural control of the stream courses throughout the area appears to be

due to strong northwest trending joints and minor normal faults. The strike of both the joints and faults is parallel to the strike of the Precambrian diabase dikes. This suggests that the post-Ordovician structural adjustments took place along a Precambrian "grain." A strong structural control of topography by northwest and northeast trending joints and minor faults has been noted in southern Ellesmere Island by Bentham (1941, p. 37).

PRECAMBRIAN

Precambrian rocks crop out beneath the Paleozoic sediments along the coast a short distance west of Dundas Harbour and they form most of the surface rocks east of the harbor, where the Paleozoic rocks have been eroded except for scattered outliers. The Precambrian rocks consist of pinkish gray, coarse-grained granites having little foliation, dark gray, medium-grained, garnetiferous gneisses with conspicuous banding, and dull red, fine-grained, thinly banded, gneissoid quartzites.

Several vertical northwest trending diabase dikes cut the metamorphic and granitic rocks. The most conspicuous dike is exposed from Walrus Point to Nadlo Point. This dike ranges from 60 to 120 feet wide. On the west side of Dundas Harbour and on strike with the dike are two thinner dikes which cut through the older Precambrian rocks and extend to the Cambrian unconformity.

STRATIGRAPHY

The limited time available for field work in 1949 did not permit a study to be made of the youngest Paleozoic rocks exposed in the area. Approximately 3,660 feet of strata were measured from the Precambrian unconformity on the west side of Dundas Harbour in the area north of Rabbit Point. Three overlapping sections were studied. The location of the measured sections is shown on figure 2. Section I extended from the upper part of the Ooyahgah formation to the upper part of the Nadlo Point limestone. Section II extended from the upper part of the Nadlo Point limestone into the Croker Bay limestone. Section III extended from the Precambrian to the lower part of the Mingo River limestone. Key beds were used in the short distance between sections to determine the continuity of the stratigraphic sequence.

The stratigraphic sequence is shown diagrammatically on figure 3. All of the formational names are new. Except for the Croker Bay limestone, the formational names were taken from local names near Dundas Harbour and are shown on figure 2. Croker Bay is a broad fiord which lies immediately west of Dundas Harbour.

Description of Formations

The lower Paleozoic rocks can be divided into six lithologic units, ranging from the Middle Ordovician Croker Bay limestone to the Lower Cambrian Rabbit Point sandstone. The type sections are given below.

Middle Ordovician

Croker Bay limestone. Type section measured along northern three-quarters of line 2, figure 2.

	Thickness in feet
Limestone, light brownish gray, fine-grained, medium- to thin-bedded. This unit extends to the top of the ridge immediately west of Mingo River. Abundant loose blocks show strong lithologic similarity to underlying beds. *Maclurites* and *Receptaculites arcticus* found at the summit of the ridge appear to have been derived from beds forming the top part of the ridge. Bottom few feet probably shaly. Unit forms steep slopes....	1100.0
Limestone, light brownish gray, very fine-grained, thin- to medium-bedded. Weathers yellowish gray and has a petroliferous odor. Top of unit forms structural terrace at locality of measured section	24.0
Covered, appears to consist of limestone and shaly limestone	28.0
Limestone, light brownish gray, fine-grained, mottled with silt, coarsely crystalline in upper part. Thin and irregularly bedded, weathers yellowish gray. Basal part contains several thin conglomerate layers of well rounded limestone pebbles. A limestone bed 6 feet thick containing chert nodules occurs 60 feet above the base	83.5
Limestone, light brownish gray, fine-grained, thin-bedded, weathers brownish gray. Contains two thin conglomerate layers of well rounded limestone pebbles	2.5
Limestone, light brownish gray, fine-grained, thin-bedded. Contains two flat pebble conglomerate layers approximately .5 feet thick, and two algal limestone beds each approximately 2 feet thick	23.5
Covered, appears to be calcareous shale	3.5

	Thickness in feet
Conglomerate-breccia, brownish gray, contains flat limestone pebbles, angular chert fragments, whole and broken chert nodules embedded in a calcareous matrix. The upper part is relatively free of chert and contains broken and bent shaly limestone layers. Lower contact is irregular	4.5
Shale, medium gray, slightly calcareous. Contains prominent algal colonies of fine-grained, dense, reddish brown limestone which have a petroliferous odor. Weathers light brownish gray	32.5
Limestone, brown, finely-crystalline, silty, medium-bedded. Weathers light yellowish gray	5.5
Limestone, light gray to brown, fine-grained, medium- to thin-bedded. Contains layers of laminated limestone with a petroliferous odor, shaly limestones, and in the basal part a thin flat pebble conglomerate	15.0
Covered, appears to be underlain by gray, platy dolomitic limestone	4.0
Limestone, brownish gray, fine-grained, crystalline, thin and irregularly bedded, has petroliferous odor. Weathers grayish brown	5.5
Limestone, brown, fine-grained, mottled with silt, nodular, medium-bedded. Weathers light brownish gray. Contains scattered chert nodules in upper part	14.5
Limestone, brownish gray, fine-grained, nodular, medium-bedded with silty partings. Weathers brown and forms subdued slope. Contains *Maclurites* in *fossil collection 2.4*	6.0
Limestone, dolomitic in part, brownish gray, medium- to thin-bedded. Contains a thin green shale bed near the base and a 5.5 foot limestone conglomerate bed containing *Isotelus* approximately 10 feet above the base	88.0
Total measured thickness Croker Bay limestone	1390.5

The Croker Bay limestone forms a prominent set of cliffs that can be traced westward at least as far as Croker Bay. The limestones forming the upper half of the section form the strongest cliffs. The top of the formation was not studied and therefore the description given above refers only to the lower part of the formation. The formation contains numerous minor diastems as indicated by thin flat pebble limestone conglomerates. Characteristic fossils are *Receptaculites arcticus*, *Maclurites* and *Isotelus*. These indicate a Middle Ordovician or possibly early Upper Ordovician age for the formation.

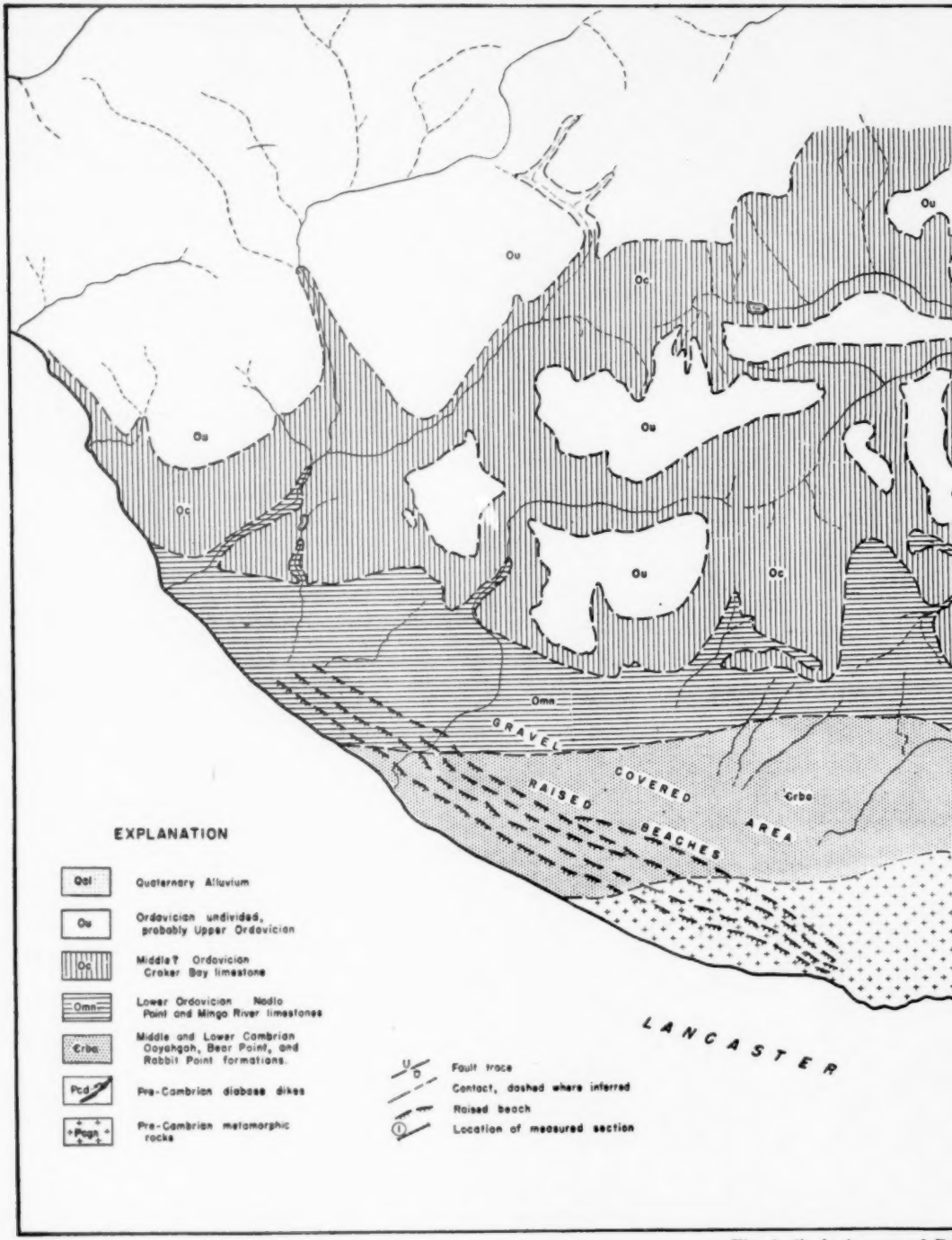
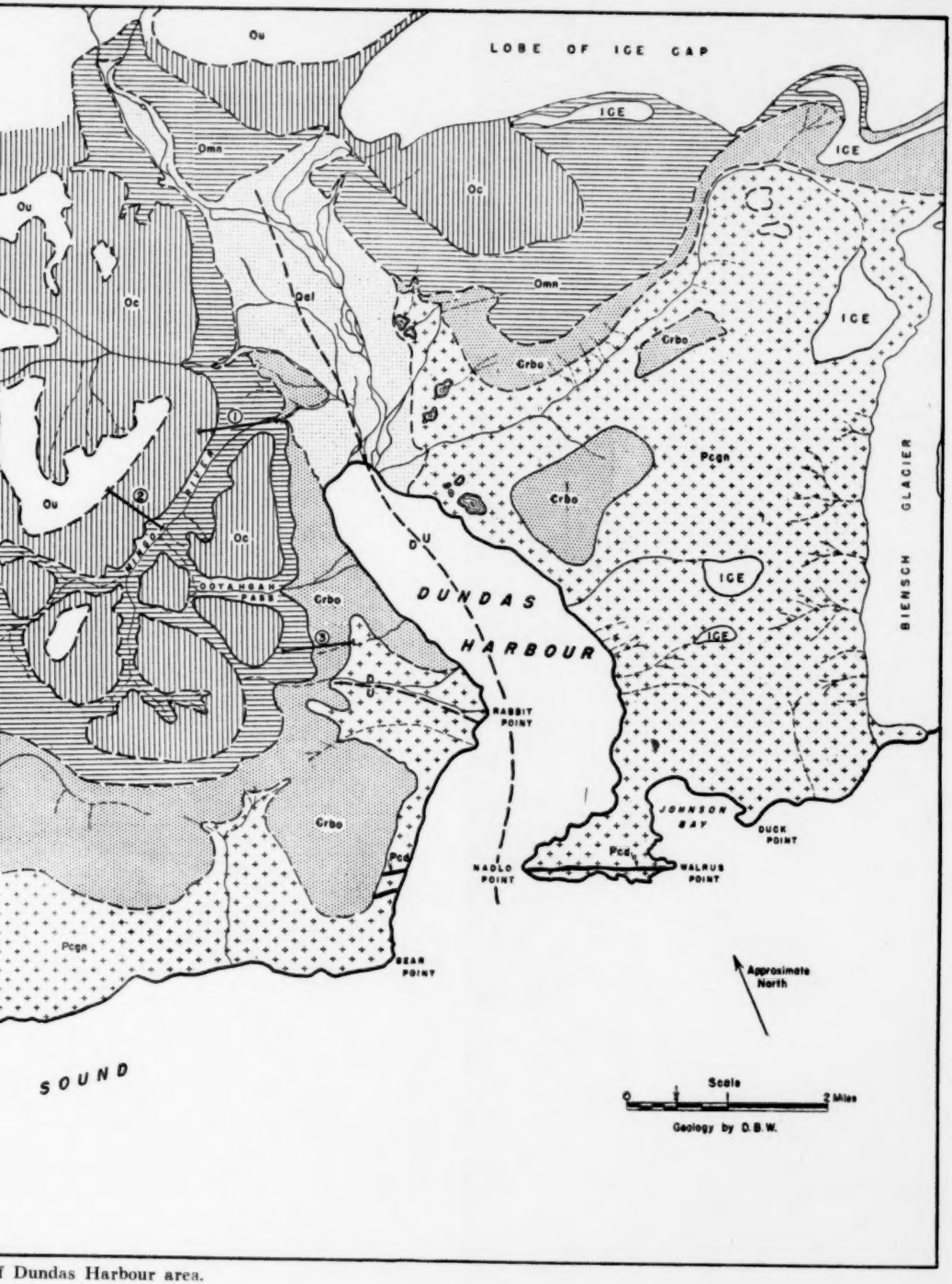


Fig. 2. Geologic map of Du



f Dundas Harbour area.

Lower Ordovician

Nadlo Point limestone. Type section measured along middle point of line 1, figure 2.

The Nadlo Point limestone conformably underlies the Croker Bay limestone. The two formations are similar lithologically but the Nadlo Point contains appreciably larger amounts of dolomitic limestone than the Croker Bay, and many beds have a reddish brown color.

	Thickness in feet
Limestone, dolomitic, gray, platy with silty partings. Forms talus covered slope	11.0
Limestone, light brown, fine-grained, thin-bedded, fossiliferous, contains a few mud cracks. Weathers light yellowish brown	7.0
Limestone, brownish gray, fine-grained, massive, dense, fossiliferous. Probably algal in origin. Weathers light brownish gray and is resistant to erosion	4.5
Limestone, brownish gray, nodular, with silty partings. Middle part contains chert nodules. Weathers light brownish gray	5.0
Limestone, grayish brown, nodular and irregularly bedded with silty partings. Weathers light grayish brown with irregular yellowish brown bands	2.0
Limestone, brownish gray, finely crystalline, irregularly bedded, contains algal structures and has a petroliferous odor. Weathers light brownish gray	8.5
Limestone, light to dark brown, nodular, mottled with silt, fine-grained, thin- and irregularly bedded with alternating light and dark layers. Upper part has a purple-brown cast	7.0
Conglomerate-breccia, light gray, consists of flat limestone pebbles and angular chert fragments and rounded chert nodules up to 6 inches long embedded in a limestone matrix. Weathers light yellowish brown.	0.5
Limestone, light yellowish brown, fine-grained, thin-bedded with silty partings. Weathers light brownish gray.	1.0
Limestone, reddish brown, fine-grained, laminated toward base, massive toward top. Weathers light brownish gray	4.5
Limestone, light yellowish brown, fine-grained, nodular with silty partings. Weathers light olive gray	0.5
Limestone, dark brown, nodular with silty partings, weathers light gray	6.0
Limestone, light grayish brown, fine-grained, silty, thin-bedded, weathers grayish brown	1.5
Limestone, brownish gray, fine-grained, nodular, medium- and irregularly bedded with silty partings. Weathers brownish gray. *Fossil collection 2.3* (*Hystricurus crassilimbatus*)	1.0
Limestone, light brownish gray, arenaceous, thin-bedded, weathers whitish gray	11.0

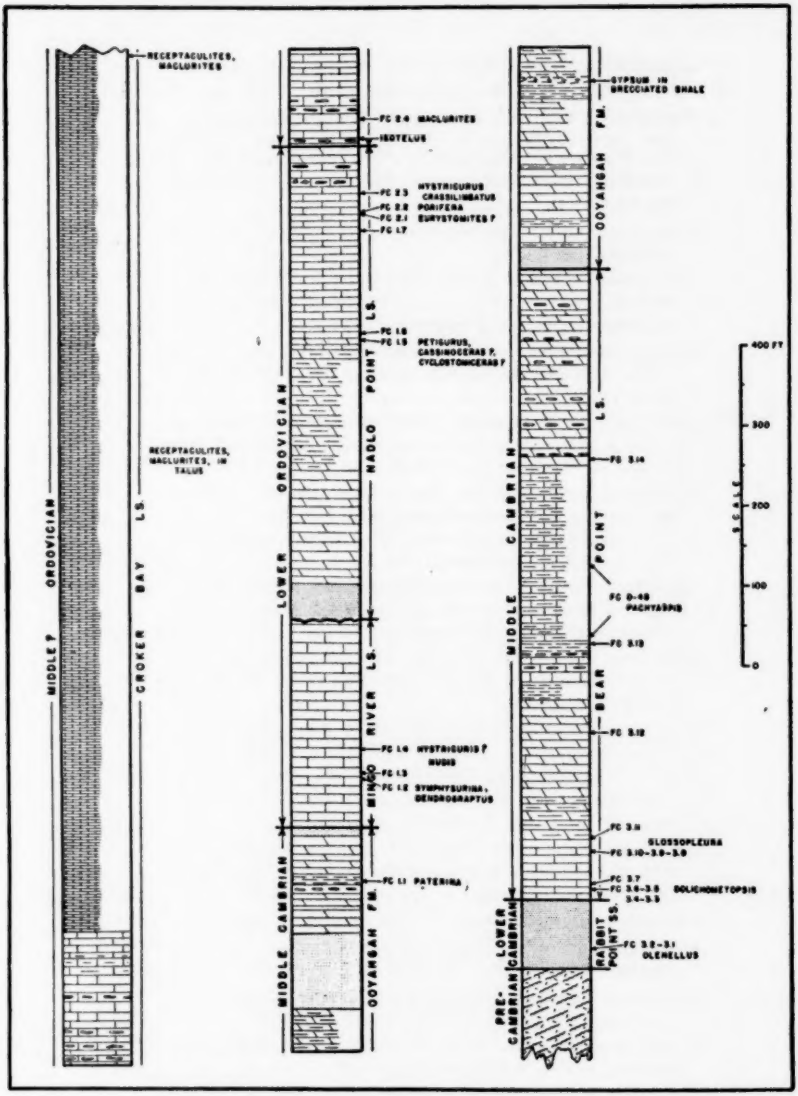


Fig. 3. Diagram showing sequence of Cambrian and Ordovician formations at Dundas Harbour.

	Thickness in feet	
Limestone, dolomitic, light brown, fine-grained, medium- to thick-bedded. Weathers light gray	4.5	
Limestone, dolomitic, dark yellowish brown, nodular, thin- and irregularly bedded becoming platy toward top. *Fossil collections 2 and 2.1* (*Ceratopea* and *Eurystomites?*) made 3.3 and 4.0 feet respectively below top of unit	10.0	
Limestone, light brownish gray, fine-grained, massive, weathers light gray	5.0	
Limestone, reddish brown, fine-grained, thin-bedded, nodular. Contains alternating bands of siltstone and dolomitic limestone. Forms subdued slope	13.5	
Breccia, yellowish gray, consisting of angular chert fragments in a calcareous silty matrix. Weathers brownish gray	1.0	
Limestone, light brownish gray, fine-grained, massive, mottled with silt, weathers brownish gray. *Fossil collection 1.7* from upper 2 feet	30.0	
Limestone, reddish brown, fine-grained, medium-bedded to massive, has petroliferous odor. Weathers gray. Chert nodules in basal 3 feet. Flat pebble conglomerates scattered throughout unit	99.0	
Limestone, reddish brown, fine-grained, petroliferous odor. Weathers brownish gray. *Fossil collection 1.6* (*Petigurus* and *Cassinoceras?*)	4.2	
Limestone, light brownish gray, silty, fine-grained, thin-bedded, fractured, has petroliferous odor. Weathers yellowish brown	1.5	
Limestone, reddish brown, dolomitic, fine-grained, has petroliferous odor, weathers light gray. *Fossil collection 1.5* (*Petigurus, Cyclostomiceras?, Ceratopea*)	3.5	
Limestone, grayish brown, silty, fine-grained, mottled with silt, weathers light olive gray	3.0	
Limestone, light olive gray, silty, fine-grained, mottled with silt patches, has petroliferous odor. Weathers light yellowish brown	6.0	
Covered, appears to consist of shaly dolomitic limestone.	150.0	
Limestone, yellowish gray, silty, fine-grained, porous, weathers light gray	5.0	
Limestone, dolomitic, brownish gray, porous, weathers light gray and forms moderately gentle slopes	72.5	
Limestone, dolomitic, light brownish gray, silty, fine-grained, shaly. Weathers orange gray	63.5	
Sandstone, greenish gray, calcareous, fine-grained, thin-bedded, weathers light olive gray. Contains glauconite in middle part and marcasite in the lower 8 feet	47.0	
Total thickness Nadlo Point limestone		590.0

The upper 250 feet of the Nadlo Point limestone forms three conspicuous cliffs separated from each other by relatively thin, less resistant limestones. The cephalopods collected from the Nadlo Point limestone were examined by Professor A. K. Miller, who reports that some of the specimens are reminiscent of the genera *Cassinoceras*, *Cyclostomiceras*, and *Eurystomites*. These genera occur in the Lower Ordovician Cassin limestone of the Lake Champlain region. The presence of *Petigurus* and *Ceratopea?* also suggest a Lower Ordovician and probably upper Canadian age for the formation. A prominent sandstone marks the base of the formation and separates it from the cliff-forming limestones of the Mingo River formation.

Lower Ordovician

Mingo River limestone. Type section measured along eastern quarter of line 1, figure 2.

	Thickness in feet
Limestone, dolomitic, arenaceous, light brownish gray, fine-grained, mottled with silt, weathers yellowish gray. Upper contact irregular with evidence of solution activity, indicating disconformity between this unit and the overlying sandstone	13.0
Limestone, brownish gray, crystalline, fine-grained, massive, weathers yellowish brown. Broad light colored bands, discernible from a distance, occur in the middle part of the unit. The lower 5 feet are less resistant than the cliff-forming upper part. *Fossil collection 1.4*, 28 feet above base, contains *Hystricurus? nudus*	176.0
Shale, calcareous, light greenish gray, nodular, irregularly bedded, weathers greenish gray. *Fossil collection 1.3*	2.0
Limestone, light brownish gray, fine-grained, mottled with silt, weathers yellowish brown	4.5
Shale, greenish gray, irregularly bedded, weathers yellowish green. *Fossil collection 1.2* contains *Symphysurina*, and *Dendrograptus gracilis?*	0.5
Limestone, light brownish gray, crystalline, medium-grained, mottled, massive, weathers light yellowish brown	7.0
Shale, greenish gray, irregularly bedded, contains limestone nodules, weathers yellowish green	1.5
Limestone, yellowish brown, fine-grained, irregularly bedded. Contains several lenticular conglomerate beds consisting of rounded flat dolomitic limestone pebbles. Separated from underlying sandstone by an abrupt contact. Forms steep cliffs	56.0
Total thickness Mingo River limestone	260.5

The thick-bedded limestones of the Mingo River formation weather into conspicuous cliffs that are steeper than the interrupted cliffs of the Nadlo Point limestone. The formation is a distinct lithologic unit, separated from the Nadlo Point by a disconformity at the top and from the Middle Cambrian by an abrupt change in lithology. The age of the formation is probably lower Canadian, as shown by *Symphysurina* and *Hystricurus*, and by its position below the Nadlo Point limestone.

Middle Cambrian

Ooyahgah formation. Type section measured along middle part of line 3, figure 2.

	Thickness in feet
Sandstone, calcareous, medium gray, coarse-grained, firmly cemented. Weathers light brownish gray. Contains shaly sandstone as a thin stringer 1.5 feet above the base. Has gradational contact with underlying limestones	9.0
Limestone, dolomitic, medium gray, medium- to thin-bedded, fine-grained, weathers whitish yellow and forms cliffs	20.0
Limestone, dolomitic, light medium gray, partly arenaceous, fine-grained, weathers whitish gray	27.5
Shale, dolomitic, very light to medium gray, arenaceous, contains a thin chert nodule zone and mudcracks and ripple-marks. Upper part contains cryptozoan colonies. *Fossil collection 1.1* was made 2.3 feet above base of unit and contains *Paterina* representing highest Middle Cambrian fossils obtained in the section	12.5
Sandstone, slightly calcareous, light gray, medium-grained, equigranular, medium-bedded with thin shaly partings. A greenish-gray shale layer 0.5 feet thick occurs at the base. Weathers light olive gray	3.5
Sandstone, highly calcareous, light gray, medium- to fine-grained, equigranular, irregularly bedded. The basal part is poorly cemented and contains large flat shale pebbles. The upper 2 feet contains thin flat limestone pebble conglomerates. Weathers light greenish gray	7.5
Limestone, dolomitic, light brownish gray, arenaceous, medium-grained, thick-bedded, weathers yellowish brown	4.0
Covered	12.5
Sandstone, dolomitic, light gray, medium- to fine-grained, thin-bedded, fractures easily, weathers greenish gray.	3.0
Limestone, dolomitic, medium gray, very fine-grained, weathers light greenish gray	3.0
Shale, medium gray, fractures easily, weathers medium gray	2.5

	Thickness in feet
Covered	12.5
Limestone, dolomitic, light brownish gray, arenaceous, medium- to fine-grained, irregularly bedded at base.	10.5
Sandstone, light brownish gray, medium-grained, cross-bedded, upper part is ferruginous and weathers dark brown	17.0
Shale, dolomitic, medium-grained	3.0
Sandstone, light gray, medium-grained	2.5
Shale, dolomitic, arenaceous, light brownish gray	1.0
Sandstone, dolomitic, whitish gray, medium-grained, firmly cemented. Contains thin conglomerates of dolomitic limestone pebbles	22.0
Sandstone, whitish gray, medium-grained, weathers light, yellowish brown. Forms poor exposures. Contains linguloid brachiopods near top	48.5
Shale and dolomitic limestone, forms talus-covered slopes. Massive and crystalline gypsum approximately 2 feet thick in brecciated shale 92 feet above base of unit. Six feet below gypsum is an 11-foot bed of greenish-gray micaceous shale	185.0
Limestone, dolomitic, medium gray, fine-grained, thin- and irregularly bedded. Contains thin flat pebble conglomerates and a 3-foot edgewise conglomerate 15 feet above base. A 5.5-foot bed of shale occurs 9.5 feet from top. Unit weathers brownish gray and forms moderate cliffs	79.5
Limestone, dolomitic, medium gray, fine-grained, thin-bedded, grading upward into dark gray, fissile, purplish weathering shale	3.5
Shale, dark gray, fissile, weathers purplish gray, interbedded with medium gray dolomitic limestone	7.0
Limestone, dolomitic, medium gray, fine-grained, thin-bedded. Contains a dark gray, fissile shale bed one foot thick near middle	4.5
Shale, medium gray to purplish gray, contains several thin dolomitic limestone beds	7.5
Limestone, dolomitic, fissile gray shale, and limestone conglomerate. Most beds have a purple cast and weather olive gray	11.5
Shale, gray with purple banding, fissile, contains thin beds of gray dolomitic limestone	4.5
Sandstone, medium gray, weathers light olive gray. Contains two thin layers of dark gray thin-bedded dolomitic limestone. Unit is very resistant to erosion and forms a steep slope	29.5
Total thickness Ooyahgah formation	554.5

The Ooyahgah formation is separated from the overlying Mingo River limestone by a distinct disconformity. A cliff-forming sandstone approximately 30 feet thick permits recognition of the base of the formation. The characteristic lithol-

ogy of the unit consists of dolomitic limestones alternating with calcareous sandstones and shales. Many of the beds contain flat pebble conglomerates. The presence of Middle Cambrian brachiopods 58 feet below the unconformity between it and the Lower Ordovician Mingo River suggests that upper Cambrian rocks are missing from the Dundas Harbour area.

Middle Cambrian

Bear Point limestone. Type section measured along middle part of line 3, figure 2.

	Thickness in feet
Limestone, shaly and dolomitic, medium gray, thin-bedded, weathers yellowish gray	10.0
Limestone, dolomitic, dark gray, medium- to thin-bedded, contains thin gray shale beds and flat pebble conglomerates. Forms poor exposures	95.5
Limestone, dolomitic, light olive gray, medium- to thin-bedded, fine-grained. Weathers light gray. Contains layers of nodular dolomitic limestone with green shaly partings and several thin flat pebble conglomerates	12.5
Covered	37.0
Limestone, dolomitic, dark gray, silty, nodular, thin and irregularly bedded. Contains a 0.4 foot conglomerate at the top	8.0
Covered	64.0
Limestone, dolomitic, medium gray, fine-grained, medium-bedded at the base becoming thin-bedded toward top. A 0.1 to 1.0 foot thick flat pebble conglomerate occurs at top of unit. *Fossil collection 3.14*	16.0
Covered, appears to be underlain by gray limy shale. *Fossil collection D-48* (not in measured section) occurs somewhat below middle of unit. Contains *Pachyaspis* faunule	217.5
Shale, calcareous, dark greenish gray, nodular, fissile, contains flat pebble limestone conglomerate layers. *Fossil collection 3.13* from upper 14 feet of unit	20.5
Limestone, dolomitic and dark gray fissile shale, weathers greenish gray and contains several flat pebble conglomerates	21.0
Limestone, dolomitic, medium gray, medium- to thin-bedded, contains a thin flat pebble conglomerate with pebbles up to 5 inches in diameter at top. Lower part consists of greenish gray, fissile, micaceous shale	9.5
Covered	22.0
Sandstone, dolomitic, yellowish gray, fine-grained, shaly, thin- and irregularly bedded. Weathers pale yellowish brown. Prominent fucoid markings	3.5
Limestone, dolomitic, pale brown to brownish gray, crystalline, silty, thin- and irregularly bedded, fine-grained. *Fossil collection 3.12*	37.5

	Thickness in feet	
Limestone, dolomitic, pale brown, crystalline, silty, thick-bedded, fine-grained. Weathers grayish orange	13.0	
Covered	54.5	
Limestone, dolomitic, pale brown, fine-grained, crystalline, silty in upper part. Weathers grayish orange	13.0	
Limestone, pale brown, massive, thin- and irregularly bedded, with silty partings. Weathers greenish brown.	16.0	
Covered	36.5	
Limestone, grayish brown, mottled, silty, nodular, thin- and irregularly bedded, has petroliferous odor on fresh fracture. Weathers yellowish gray. *Fossil collection 3.11* was made from upper part of unit, contains *Glossopleura* faunule	4.5	
Covered	6.0	
Limestone, grayish brown, nodular, medium- to thin-bedded, with silty partings. A bed containing abundant marcasite occurs near the base. *Fossil collection 3.10* was made from the upper two-thirds of the unit. *Collections 3.9* and *3.8* were made from the basal third of the unit. *Glossopleura* faunule	9.0	
Covered	23.0	
Limestone, pale brown, nodular, medium- to thin-bedded, with silty partings. Upper part contains chert	2.0	
Limestone, brownish gray, fine-grained, mottled with silt, has petroliferous odor on fresh fracture	4.0	
Covered	5.0	
Limestone, brownish gray, nodular, irregularly bedded, fine-grained. *Fossil collection 3.7* was made from the uppermost 6.4 feet of the unit. *Collections 3.6, 3.5, 3.4* and *3.3* were made 18.5, 10, 6.9, 4.2 feet respectively above the base of the unit. The collections contain the *Dolichometopsis* faunule	25.0	
Total thickness Bear Point limestone		786.0

The Bear Point limestone contains numerous thin, flat, pebble conglomerates and clastic zones indicating a shallow water depositional environment with numerous periods of non-deposition. The formation forms moderate slopes in contrast to the younger cliff-making limestones. The fossils indicate an early Middle Cambrian age for the formation.

Lower Cambrian

Rabbit Point sandstone. Type section measured above Precambrian contact, eastern end of line 3, figure 2.

	Thickness in feet
Covered, appears to consist of gray, fine-grained sandstone	50.0

	Thickness in feet	
Sandstone, calcareous, light greenish gray, fine-grained, contains abundant vertical tubes of *Scolithus* which range from 1 to 2 mm. in diameter and contain glauconite grains around the periphery of the tubes. Unit weathers light grayish brown	2.5	
Covered, apparently consists of gray sandstone	6.0	
Sandstone, glauconitic, light grayish green, medium-grained, with numerous white calcareous fossil fragments. Weathers light greenish brown. *Fossil collection 3.2*	1.0	
Covered	2.5	
Sandstone, calcareous, glauconitic, pale red, mottled with grayish green, medium-grained. Contains worm borings. *Fossil collection 3.1* contains *Olenellus* and linguloid brachiopods	0.5	
Covered, appears to consist of red and gray sandstone. Rests with angular discordance on Precambrian crystallines	23.5	
Total thickness Rabbit Point sandstone		86.0

The Rabbit Point sandstone consists of clastics deposited during the Lower Cambrian transgression over an essentially peneplaned Precambrian surface. The formation is not resistant to erosion and forms poor exposures. The presence of *Olenellus* indicates a Lower Cambrian age for the formation.

Stratigraphic Summary

The geographical remoteness of Dundas Harbour from other areas that have been studied in the Canadian Arctic does not permit detailed comparison of its stratigraphic section with other areas. The nearest place in which even reconnaissance work has been done is southwestern Ellesmereland. Here Schei (1904, pp. 457-460) described a generalized section of Lower Paleozoic rocks. Apparently Schei had little opportunity to study in detail the lower part of his section and as a result no accurate comparison can be made except to suggest that the Cambrian and Ordovician rocks described in the present paper are apparently the stratigraphic equivalents of the lower half of Schei's Series A.

The works of Poulsen (1946, pp. 299-337) and Troelsen, 1950, pp. 37-60) bring together much information on the Cambrian and Ordovician rocks bordering Kane Basin, where relatively good sections are exposed on Inglefield Land in northwest Greenland and in the vicinity of Bache Peninsula

in east Central Ellesmere Island. Although Kane Basin is approximately 300 miles north of Dundas Harbour, many similarities can be noted in the fossil zones, and to a lesser extent, in the lithology of the Cambro-Ordovician rocks of the two areas. A comparison of the rocks and faunal assemblages are shown in table 1.

The Lower Cambrian Rabbit Point sandstone is regarded as the basal clastic deposit of advancing seas that reached the Dundas Harbour area shortly before the close of Lower Cambrian time. This basal sandstone is not considered to be either the lithologic or age equivalent of the thin Police Post limestone and Wulff River formation of Kane Basin. The Cape Kent oolitic limestone best developed on Inglefield Land contains both the *Olenellus* and *Dolichometopsis* faunas. Whether the two faunas occur together or are stratigraphically separated is not evident. At Dundas Harbour the two faunas are distinct. The *Dolichometopsis* fauna is restricted to the basal 80 feet of the Bear Point limestone and contains representatives of the *Albertella* zone (Lochman, 1948) and is therefore considered lower Middle Cambrian in age. Thus the Rabbit Point sandstone containing *Olenellus*, and the *Dolichometopsis*-bearing beds of the Bear Point limestone are correlated with the Cape Kent limestone. The *Glossopleura* and *Pachyaspis* faunas from the succeeding 400 feet of the Bear Point limestone represent the *Glossopleura-Kootenia* zone of Lochman (1948). Poulsen (1946) reported the *Glossopleura*, *Elrathiella*, and *Blainiopsis* faunas from the Cape Wood formation. The latter two faunas were not found in the Dundas Harbour area and just where they fit into the faunal succession is not known at the present time.

The Ooyahgah formation can be subdivided into five lithologic units: a basal sandstone, an alternating series of shales and limestones of a cyclical nature, limestones, a series of shales and shaly dolomitic limestones with gypsum near the middle part, and sandstones with interbedded limestones at the top of the formation. The occurrence of gypsum is most significant in indicating an environment such as to permit the deposition of evaporites. Apparently the Ooyahgah formation and the upper part of the Bear Point limestone, representing approximately 940 feet of section, have no age correlatives in the Kane Basin area unless there is considerable conver-

TABLE 1

Table showing comparisons of formations and faunas of N. W. Greenland-Ellesmere Island and Devon Island

	N. W. Greenland - Ellesmere Island (Troelsen, 1950) and (Poulsen, 1927, 1946)		Devon Island Dundas Harbour	
	Formations	Faunal Assemblages	Formations	Faunal Assemblages
Middle Ordovician	Gonioceras Bay ls.	*Receptaculites* *Bumastus* *Gonioceras* *Maclurites*		*Receptaculites*
	Cape Webster fm.		Croker Bay ls.	*Maclurites* *Isotelus*
Lower Ordovician	Nunatami fm.	*Phyllograptus augustifolius*		*Hystricurus crassilimbatus*
	Cape Weber ls.	*Petigurus-Bathyurellus*	Nadlo Point ls.	*Petigurus*
	Nygaard Bay ls.	*Protocycloceras*		
	Poulsen Cliff sh.			
	Cape Clay ls.	*Symphysurina*	Mingo River ls.	*Hystricurus? nudus* *Symphysurina*
	Cass Fjord fm.			
Middle Cambrian			Ooyahgah fm.	*Paterina*
	Cape Wood fm.	*Blainiopsis* *Elrathiella*	Bear Point ls.	*Pachyaspis*
		Glossopleura *Dolichometopsis*		*Glossopleura* *Dolichometopsis*
	Cape Kent ls.			
Lower Cambrian		*Olenellus*	Rabbit Point ss.	*Olenellus*
	Wulff River fm.	*Olenellus-Kurtogonia-Salterella*		
	Police Post ls.	*Bonniopsis-Paedumius*		
	Thule Group		Precambrian crystallines	

gence of sediments between it and Dundas Harbour. It is postulated that the Dundas Harbour area was an enclosed or partially enclosed basin during the deposition of evaporites.

The Upper Cambrian sediments appear to be very thin or missing at Dundas Harbour as well as other areas bordering on the Franklinian geosyncline. The occurrence of Middle Cambrian brachiopods approximately 58 feet below the base of the Ordovician Mingo River formation and about 132 feet below the lowest occurrence of Lower Ordovician fossils suggests strongly that Upper Cambrian rocks are not present at Dundas Harbour.

The Mingo River limestone may be divided into two lithologic units, a lower part, predominately of irregularly bedded limestones with flat pebble conglomerates, and a thick upper unit of very massive limestones. The upper limestones agree in lithology and faunal content with the Cape Clay formation of Washington Land. The lower beds are probable correlatives of the uppermost beds of the thick Cass Fiord formation. This relationship suggests that a parallel condition existed in Lower Ordovician and in the Lower Cambrian, with the seas reaching Dundas Harbour later than they did the Kane Basin area.

The lower part of the Nadlo Point limestone may correspond to the Poulsen Cliff shale and Nygaard Bay limestone, as the overlying beds, the Cape Weber formation of Kane Basin and lower part of the massive limestones of the Nadlo Point formation are similar and contain a similar fauna. The upper part of the Nadlo Point limestone would then correspond to the Nunatami formation, also of Lower Ordovician age.

Apparently the Cape Webster formation corresponds to the lower part of the Croker Bay limestones as the upper part of the Croker Bay limestone and the Gonioceras Bay limestone contain some of the same diagnostic Middle Ordovician fossils.

Both areas show moderate thicknesses of sediment that reflect a foreland shelf environment with varying degrees of stability. Marked stability must have been the case when the massive homogeneous limestones of the Mingo River formation were laid down. Such was also the rule with massive beds in the Nadlo Point limestone. The blanket sands in the upper part of the Ooyahgah formation are considered to have been deposited under relatively stable conditions. On the other

hand, flat pebble conglomerates from the lower part of the Mingo River limestone and other formations indicate short periods of sea level fluctuation and many short diastems. Certainly the most profound break in the stratigraphic record is the absence of Upper Cambrian sediments.

A clue to the origin of much of the Cambro-Ordovician limestones lies in the algal colonies in the lower part of the Croker Bay limestone and upper part of the Nadlo Point limestone. The algal colonies are a reddish brown, very fine-grained, dense limestone with a petroliferous odor. This type of limestone is found in all formations with the exception of the Mingo River limestone. The percentage of algal limestone to the total amount of limestone ranges from 0 to 100. The highest percentage of algal material is in the lower part of the Croker Bay limestone and upper part of the Nadlo Point limestone with decidedly lesser amounts in the other formations. The algal colonies are generally less than a foot thick, have a smooth bottom and undulating top, and a typical algal structure. In cross section they vary from several feet to an undetermined length. Layers of shale butt up against the sides of the colonies and show a slight amount of differential compaction over them.

The relatively thin Lower Cambrian rocks indicate proximity to the Franklinian geosyncline. In the Appalachian and Cordilleran geosynclines the troughs proper contain thick Lower Cambrian rocks that thin out rapidly on the foreland. From this comparison, the thinner Lower Cambrian rocks of Dundas Harbour indicate that the area is farther from the geosyncline than the thicker Lower Cambrian section in the Kane Basin area.

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CORAL REEFS OF THE LOYALTY ISLANDS

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ABSTRACT. The Loyalty Islands are a small group of northwest-southeast trending reef islands, 60 miles northeast of New Caledonia in the south Pacific. The group is composed of three main islands, Ouvea, Lifu, and Mare, and several smaller islands. Ouvea is a coral atoll, while Lifu and Mare are believed to have resulted from growth of fringing reefs around a central core. On Mare the actual core of serpentine is exposed. The group lies on a block of the sea floor that has been uplifted and tilted, more at the southeastern end than at the northwestern. Faulting may be present along the flanks of the group and between the islands. Northwest of the group are the Astrolabe Reefs, which may be incipient atolls.

INTRODUCTION

LOCATED between 166 and 168 degrees East Longitude and 20 and 22 degrees South Latitude, the Loyalty Islands are a little known but interesting group of coral reefs. Their location in the South Pacific is shown in figure 1. The islands were first discovered by Dumont d'Urville, a French explorer, on June 15, 1827, but a complete survey of the group was not finished until 1840, and the French did not take formal possession until 1853. At present, the islands are administered from the French provincial capitol at Noumea, New Caledonia.

The islands of the group are aligned in a linear belt 145 miles long. This belt runs in a northwest-southeast direction parallel to, and approximately 60 miles northeast of New Caledonia. The three most important islands in the Loyalty group are, from northwest to southeast, Ouvea, Lifu, and Mare. All three are comparatively small and have resulted from the work of reef-building organisms. The relationship of the different islands to each other is illustrated in figure 2.

THE THREE MAIN ISLANDS

The northwesternmost island, Ouvea, is a growing coral atoll, roughly triangular in shape, 25 miles long and 24 miles wide. The southeastern rim of the atoll is the widest exposed part of the reef with a maximum width of 3½ miles. This side is also the highest part of the atoll with a maximum elevation of 50 feet above sea level. The remainder of the reef is quite low, usually less than 15 feet above sea level and less than a

mile in width. The southeastern rim is unbroken by passes or channels, but the other two sides are divided into a series of small sand islands and reef patches. Since the southeastern side is better developed than the other two and the prevailing wind in this region comes from the southeast, probably this side of the atoll developed first while the other two sides developed as horns surrounding a lagoon. The two horns almost meet at the northwest end and are separated by Anemata Pass, 3 miles wide. The deepest part of the lagoon is found just inside of this pass where a depth of 108 feet has been recorded. The depth in the central part of the lagoon averages between 45 and 48 feet, but is very irregular.

Lifu, the central of the three main islands, lies 27 miles southeast of Ouvea Atoll. It is L-shaped, with an upper arm 26 miles long and a lower one 30 miles long. The entire island is composed of dead reef material, although fringing reefs are growing along scattered sections of the coast. Lifu has a maximum elevation of 180 feet above sea level and a large part of the island is well above the 100-foot level. Extending along almost the entire coast of the island is a series of steep cliffs,

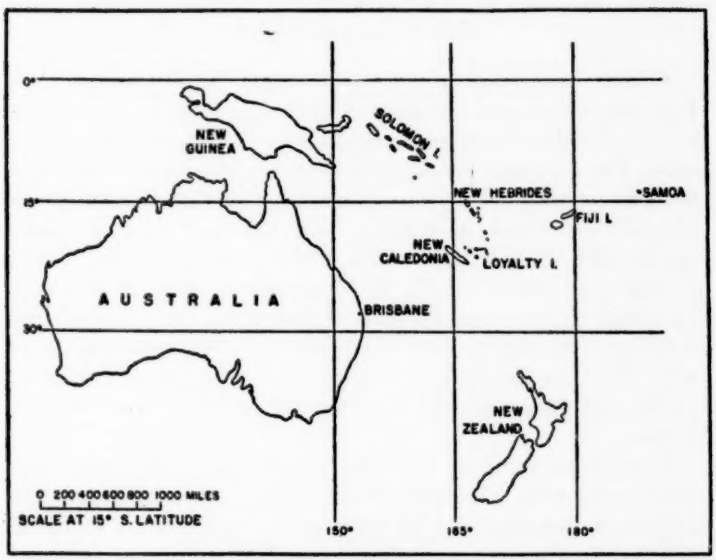

Fig. 1. Index map of southern part of Pacific Ocean showing location of Loyalty Islands.

vertical faces 50 feet high being very common. On the northwest coast between Cape Martin and Cape Lefevre is a well developed inlet known as Sandal Bay. The coastline here is flat with a few low cliffs, although the tips of both capes are 50 feet above sea level. A depth of 490 feet has been measured within the bay. Two large caves in the reef material make Lifu the most scenic of the three islands.

The island of Mare, 25 miles southeast of Lifu, is the most interesting of the three islands from a geological standpoint. The island is roughly rectangular in shape, 20 miles long and 25 miles wide. It is composed of dead reef material that has been uplifted as much as 320 feet above sea level. Growing fringing reefs are scattered along the coast. A large hill in the center of the island consists of serpentine believed to represent the platform upon which the reef grew. Unfortunately, all of the samples collected by the author from this area were lost during the course of the past war, so that no detailed information concerning this material is available. Megascopically, it is the same as the serpentine forming a large part of the island of New Caledonia.

THE SMALLER ISLANDS

Fifteen miles north of Ouvea Atoll is a smaller atoll, Beautemps-Beaupre, or Heo as it is more commonly known. Heo is roughly circular in shape and has a diameter of 15 miles. The best reef development occurs along the southeastern rim and, to a somewhat less extent, along the northeastern rim. The reef rim is unbroken along these sides and reaches a maximum width of over 2,000 feet. The remainder of the reef is divided into small islands by numerous passes or channels. The highest elevation on Heo is found on the southeastern rim, but is barely 20 feet above sea level. No soundings have been taken in the lagoon, but from a small boat numerous patches of reef material may be seen growing up from the bottom.

Four miles north of Lifu lies Jouan Reef, 2½ miles long and ½ mile wide. The reef is barely above sea level at low tide and can be located only by breakers at high tide. A depth of 840 feet has been measured between the reef and the island of Lifu.

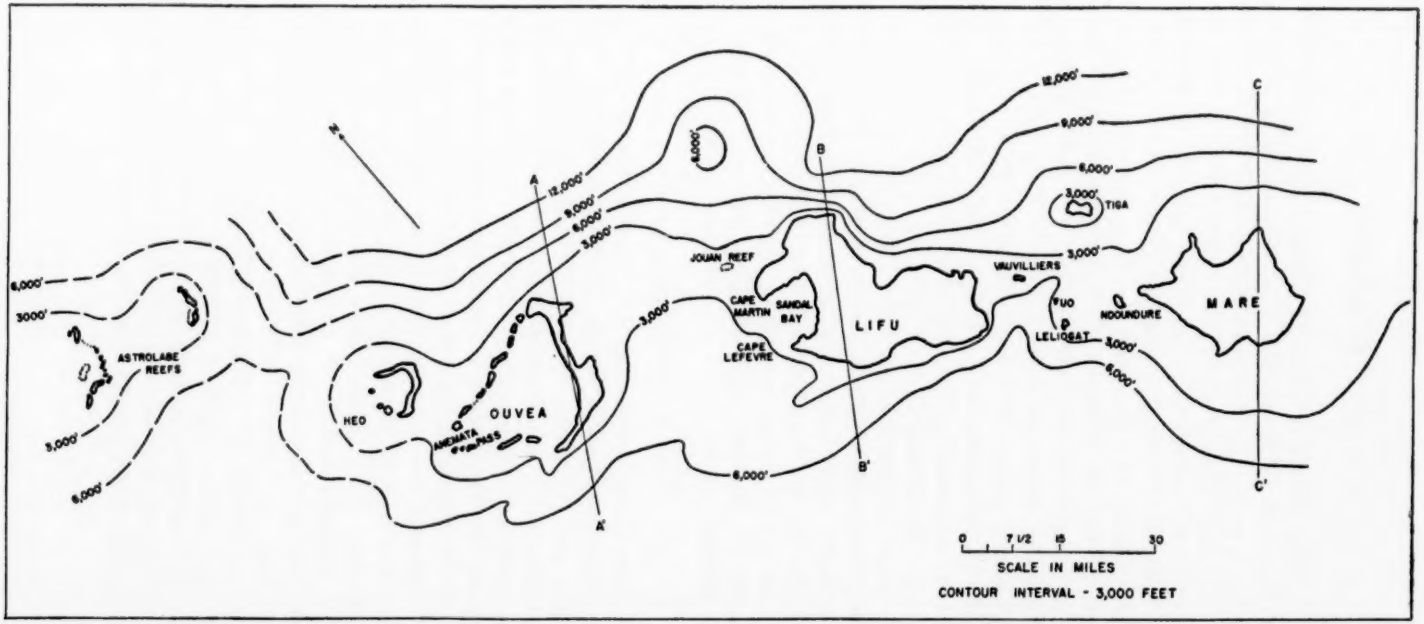

Fig. 2. Outline map of the Loyalty Islands. Dashed contour lines indicate areas of scattered soundings where contouring may be in doubt.

Five small islands are located between Lifu and Mare. The largest of these, Tiga, is 2¼ miles long and 1¼ miles wide. Tiga has a maximum elevation above sea level of 250 feet while the other four islands are all over 200 feet above sea level. All five of the islands are steep-sided, possessing little beach or none at all. No fringing reefs are growing around the edges of these islands as apparently the drop into the ocean is too abrupt to furnish a platform of any type for reef growth. All the islands are composed of dead reef material that has been uplifted above the ocean surface to its present attitude.

While not generally considered as part of the Loyalty Islands, the Astrolabe Reefs, 29 miles northwest of Heo Atoll, appear to be located on the same structural block as the Loyalty group (fig. 2) and they are included here because the same factors that affected the Loyalty Islands would also have influenced their history. The Astrolabe Reefs consist of two main ribbon reefs, one 12 miles long and the other 7 miles in length, and connected small reef patches. The reefs are less than 2,500 feet wide and barely above sea level. The main ribbon reefs have a somewhat arcuate shape which is discussed further in a later section.

THE SURROUNDING SEA FLOOR

The sea floor surrounding the Loyalty Islands presents a very interesting study in itself. Paralleling the Loyalty Islands, and lying between the Loyalty group and New Caledonia, is a relatively flat-bottomed trench in which depths of over 7,000 feet are reached within 25 miles of the islands of the group. To the northeast, the bottom drops off rapidly and a depth of 10,000 feet has been measured only 4 miles from Lifu. Between the Loyalty Islands and the New Hebrides group, 110 miles to the northeast, depths of over 22,000 feet are common. In a northeasterly direction from the Loyalty group, bottom soundings of over 5,000 feet may be obtained within 5 miles of any of the three islands, a slope of 1,000 feet to the mile.

Between Ouvea and Lifu the greatest measured depth is 5,400 feet, while a depth of 5,500 feet has been measured between Lifu and Mare although depths between 1,200 and 1,500 feet are much more common. South of Mare for almost 40 miles the greatest recorded depth is only 3,700 feet.

While the greatest depth between Jouan Reef and Lifu is 840 feet, a depth or nearly 2,000 feet was recorded less than a mile southwest of this point.

Ten miles east-southeast of Ouvea is a circular peak approximately 4 miles long and 3 miles wide that rises 1,800 feet above the sea floor. The top of this peak lies 500 feet below sea level.

Eighteen miles north of Lifu is a small sea mountain. The top of this peak is 4,800 feet below sea level and the sea mount rises 4,200 feet above the surrounding sea floor. Soundings indicate that the peak is roughly elliptical in shape and may be as much as 5 miles in diameter at its base. Unfortunately, sufficient soundings were not taken to determine the size of the top of the peak or to determine it is is flat-topped.

A small submarine canyon is found between Ouvea and Lifu heading toward the deeper part of the ocean in a southwesterly direction. A small ridge connects the two islands and separates this canyon from a somewhat smaller one on the northeast side of the narrow ridge.

Figure 2 also shows the contours drawn on the sea floor of the area surrounding the Loyalty Islands. The area was contoured from a large number of soundings taken by the United States and French navies during World War II. The region between Ouvea and the Astrolabe Reefs was lightly sounded and poorly charted so that the contouring in this area may be in doubt.

Figure 3 shows a series of three profiles constructed at right angles to the trend of the main islands. These profiles show the extremely steep northeastern slope of Ouvea and Lifu and the more gentle southwestern slopes. Both flanks of Mare slope more gently than do the sides of the other two islands.

ORIGIN OF THE LOYALTY ISLANDS

In his excellent but generally unavailable papers, W. M. Davis (1917, 1925, 1928) states the theory that Mare and Lifu are uplifted atolls. The author cannot agree completely with this idea. Part of Lifu has an atoll configuration, but not Mare. The northwestern part of Lifu, including Sandal Bay and Capes Martin and Lefevre, is definitely atoll-like. Here, Sandal Bay represents the old lagoon and Capes Martin and Lefevre are the horns partially surrounding the lagoon. The

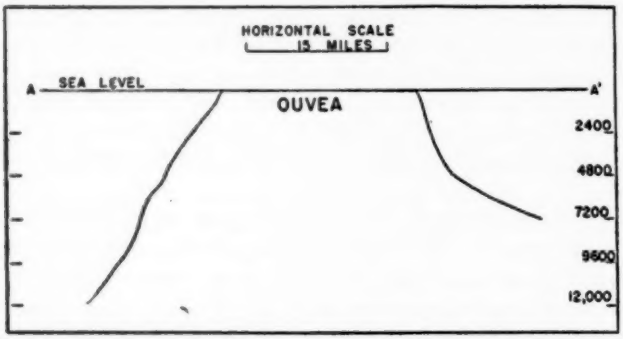

Fig. 3A. Profile constructed across Ouvea Atoll and surrounding sea floor. Vertical exaggeration approximately 10 X.

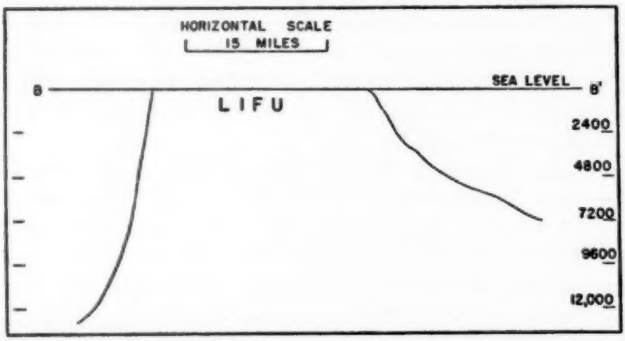

Fig. 3B. Profile constructed across Lifu and surrounding sea floor. Vertical exaggeration approximately 10 X.

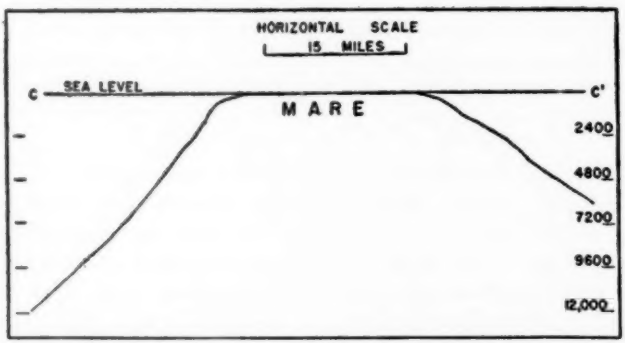

Fig. 3C. Profile constructed across Mare and surrounding sea floor. Vertical exaggeration approximately 10 X.

sea floor along the northwest side of Sandal Bay has the configuration of a sill along the seaward margin of the bay and may represent the remainder of the rim surrounding the lagoon. However, the rest of the island is rather flat, rising slowly to the highest point in the center of the island, and only at Capes Martin and Lefevre is there anything like a coral rim such as might be expected if the island were an uplifted lagoon. The reef material of the island is rather massive and uniform throughout, as indicated by exploration of the caves. There is nothing resembling a lagoon surrounded by a coral rim and filled with debris and sand. Rather, one has the impression that the entire area is one massive reef. It is the author's belief that Lifu began as an atoll, but that tilting and submergence resulted in the downwarping and drowning of the northwest side of the atoll. As a platform was available to the southeast, fringing reefs began to grow there and the outline of the old atoll, plus the platform upon which it had grown, permitted growth and extension of the fringing reefs until the island reached its present size. At a later date the island was uplifted and acquired its present attitude.

Mare definitely does not resemble an atoll as no rim is present anywhere on the island and the coral material slopes upward rather gently around the central serpentine core. Again, the reef material is very massive and uniform. This is one of the few coral islands in the world that exhibits the platform rock upon which the reef grew; hence, it is believed that Mare developed from the growth of fringing reefs around a serpentine peak. Gradual submergence of this peak resulted in growth of the reef upward and inward until the present core was nearly or completely covered by reef material. Subsequent uplift and erosion resulted in the present attitude of the island. Figure 4 illustrates the mechanics of one of the possible theories to explain the origin of the island of Mare.

Ouvea developed as a good example of an atoll with a lagoon surrounded by a coral rim. Uplift of the southeastern edge exposed a wide section of reef while downwarping of the northwestern side resulted in submergence. The present appearance of the northwestern rim of the atoll is the result of this downwarping. Either the reef continued to grow upward as the platform sank, or the isolated islands are merely the tops and remnants of the reef on this side.

Heo Atoll shows less evidence of tilting or uplift than the rest of the group, but even on Heo the southeastern rim is higher and better developed than the rest of the atoll. Heo may have resulted from submergence of a larger atoll followed by upward growth of the reef on a reduced scale.

In view of the serpentine core of Mare, the Loyalty Islands may be said to have grown on the top of a northwest-southeast trending block of the sea floor. The steep flanks of the block suggest the possibility that this block was faulted up into its present position. The greatest amount of uplift occurred at the southeastern end. Although the entire block was uplifted, the amount of uplift was not uniform throughout the area; possibly cross-faults at right angles to the main trend modified the uplift, separating each of the islands and producing tilting as well as upwarping. Recent uplift gave the group its present position, for if sea level had been lowered all three of the islands would have essentially the same elevation above sea level, whereas each island actually has a different maximum and general elevation above sea level. The five small islands between Mare and Lifu may have formed in the same manner as Mare, by the growth of fringing reefs around a core which was slowly submerging, followed by recent uplift. These individual islands may be fault blocks, related to the other islands only by their position on the main northwest-southeast block. Very recent uplift is indicated by the extremely steep cliffs found on Mare, Lifu, and the five small islands between them. Beaches are narrow and poorly developed, if present. Uplift seems to have been fairly recent as, even though a good soil has developed, little effect of erosion can be noticed around the islands.

ORIGIN OF THE ASTROLABE REEFS

The Astrolabe Reefs, consisting of two main ribbon reefs and associated small reef patches, appear to be situated on another segment of the same large block as the main Loyalty group (fig. 2). The two ribbon reefs have a northeast-southwest alignment, but the tips of each reef have been bent toward the northwest. They may represent an early stage of atoll development.

To develop an atoll from ribbon reefs of this type four conditions will be necessary. First, ideal conditions for reef growth must continue; second, a prevailing wind from the southeast

must be present; third, there must be a suitable platform on the northwest side; and fourth, all of these ideal conditions must exist for a sufficient length of time. Under these four conditions, the Astrolabe Reefs will continue to grow and in time the reef tips will completely or partially enclose a lagoon. To be sure, a good platform need not be present on the northwest side as to a certain extent the reef will provide its own platform and grow upon itself. Since the entire block upon which

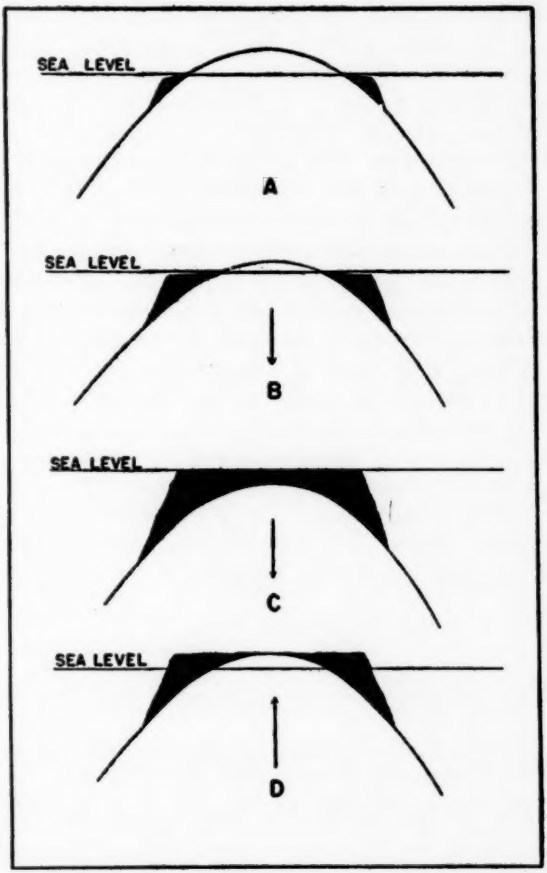

Fig. 4. Possible explanation for growth of coral reefs around Mare. Slow downwarping followed by uplift resulted in the present appearance of the island. Reefs shown in black.

this group grew was uplifted at the southeastern end and downwarped at the northwestern end, the Astrolabe Reefs may be growing on an older atoll that was downwarped. Sufficient time has not elapsed for the Astrolabe Reefs to surmount completely the ancestral reef and form a second, younger atoll.

SUMMARY

The Loyalty Islands present a very interesting picture of reef development. The Astrolabe Reefs may be classed as incipient atolls which, given sufficient time, may develop into typical coral atolls. Heo and Ouvea are examples of atoll development affected by uplift of their southeastern edges. Lifu is a solid mass of reef material with fringing reefs growing around the edges of the island. The northwestern part of Lifu may have been an atoll, but was downwarped and later uplifted. Mare has been uplifted more than the other islands in the group and has a serpentine core around which fringing reefs have grown. The entire group has been uplifted and tilted, the southeastern end being uplifted while the northwestern section was downwarped. The steep slopes of the northeastern flanks of the group may have resulted from faulting as well as from individual variations of tilting within the group. No direct evidence is available to substantiate the idea of faulting beyond the variations of tilting for each of the islands as contrasted with the other islands of the group. The coral reefs of the Loyalty Islands appear to have grown upon the top of a serpentine block, either an up-faulted block from the sea floor or a large, irregularly topped sea mountain.

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AMARILLO, TEXAS

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THE LOCALIZATION OF SODIUM SULFATE DEPOSITS IN NORTHEASTERN MONTANA AND NORTHWESTERN NORTH DAKOTA

IRVING J. WITKIND*

ABSTRACT. The sodium sulfate deposits of northeastern Montana and northwestern North Dakota are confined to depressions within the glacial drift. The alignment of the deposits, many of which are linear, suggests some form of glacial control. It is believed that the localization of these deposits is related to buried channels that have been formed marginal to the ice.

Two types of channels are recognized. One type was formed during the withdrawal of the last ice. It is filled with sand and gravel and, as far as known, contains no exploitable sodium sulfate deposits. The other type of channel was formed during a temporary stillstand of the ice and was later buried beneath till of a renewed advance. In places, the till was thick enough to fill completely the former channels. Elsewhere, the till merely surfaced the channels. These elongate, till-surfaced swales, which conceal channel sediments, trend irregularly across the area, and contain commercial deposits of sodium sulfate in depressions within them. The alignment of the deposits results from their position within the till-surfaced channels.

It is thought that the buried channel sediments contain the sulfate-rich waters under artesian head, and that these waters locally escape upwards into the depressions of the till-surfaced swales where evaporation causes concentration.

INTRODUCTION

DURING the summers of 1946 to 1948 the U. S. Geological Survey mapped a large area including parts of Sheridan and Roosevelt Counties in northeastern Montana and parts of Divide and Williams Counties in northwestern North Dakota. This work was part of the Geological Survey investigations in the Missouri River Basin.

In the course of the work I became interested in the numerous sodium sulfate (Glauber's salt) deposits in the eastern half of the area (plate 1). Many of these deposits are so aligned as to suggest more than mere coincidence in their location. The field work indicated an intimate relationship between the locations of the saline deposits and the glacial history. This paper presents an hypothesis to explain the location and pattern shown by many of these deposits.

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ACKNOWLEDGMENTS

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Sol Meltzer capably assisted me during the summer of 1948, when many of the ideas incorporated in this paper were being formulated, and to him also I extend my sincere thanks and appreciation.

BEDROCK STRATIGRAPHY AND STRUCTURE

The Fort Union formation of Paleocene age underlies the surficial deposits. In general, the Fort Union strata consist of silt, clay, shale, sandstone, and some lenticular lignite beds. Laterally, the strata change facies rapidly and marker horizons are practically nonexistent.

This area is along the northwest margin of the structural Williston Basin, and the regional dip is southeastward at about 20 feet to the mile. Little evidence is available to suggest local deformation. Townsend (1950, p. 1552), however, has reported some local deformation of the Fort Union formation in an area northeast of this locality.

SURFICIAL DEPOSITS

The area is mantled by thick and extensive deposits of glacial debris. As yet, it is not known how many times continental glaciers advanced across the area; field evidence in adjacent areas (Howard, 1950) suggests at least three, and possibly four separate advances. The age of these advances is uncertain, although the last three are probably Wisconsin.

The topography has been modified by glacial erosion of the high places and deposition in the low places. The area is a broad, till-covered upland, traversed by wide outwash-filled valleys.

The till is a compact clayey mass, light buff on outcrop. It ranges in thickness from a thin film to much more than 100 feet, and is completely unsorted. Rock debris from the Canadian Shield, ranging in size from fine sand to boulders as much as 10 feet in diameter, is embedded in the till and mantles its

surface. Included with the debris, however, are large amounts of brown, well-rounded pebbles of quartz, quartzite, and chert, characteristic of the Flaxville Plain (Collier and Thom, 1918, p. 179).

Similar debris, although better sorted and completely unconsolidated, floors many of the outwash channels. Pebbles of limestone, granite, gneiss, and schist predominate.

Till and bedrock alternate irregularly along valley walls suggesting that, in places, the present valleys lie astride the sinuous courses of former channels now filled with till.

MODE OF OCCURRENCE OF SODIUM SULFATE DEPOSITS

The geological setting of the sodium sulfate deposits in eastern Montana and northwestern North Dakota is essentially the same as in Saskatchewan (Grossman, 1949, p. 8).

All the deposits, whether small or large, are in undrained depressions. Surface drainage is inward, although the numerous springs in and around the flanks of the deposits probably supply most of the lake water. Many of the springs feeding the saline sloughs are highly charged with sodium sulfate. Cole (1926, p. 76) passed a metal tube down the orifice of one of the Saskatchewan springs. The water that rose in the pipe was only slightly charged with sodium sulfate. This suggests that some of the springs may acquire their high sodium sulfate content as they pass upward through a buried sodium sulfate bed. Cole (1926, p. 83) reports a second type of spring that differs in having a much greater concentration of salines. These are called "true brine springs," and their source waters apparently are highly charged with salines before reaching the buried sodium sulfate deposits.

The salines are concentrated chiefly by evaporation in these basins. When the rate of evaporation surpasses that of inflow, the lakes become saturated with sodium sulfate and crystals are deposited. A rise in temperature or addition of water will cause the crystals to redissolve. Hence, such precipitation may give rise to what is known as "the intermittent bed." With long-continued uninterrupted precipitation a more massive deposit accumulates, not so susceptible to local variations in temperature or rainfall. Such a bed is called "the permanent bed." A major deposit of sodium sulfate may have permanent beds as thick as 70 feet (Lavine and Feinstein, undated, p. 5).

The origin of the sodium and sulfate components is unknown. They may be derived from the underlying Fort Union formation, from the till, or from both.

ALIGNMENTS OF SALINE DEPOSITS

The deposits within the United States align with those in Saskatchewan in a northwestward-trending zone, about 30 miles wide, more or less parallel to the so-called Altamont moraine. Whether this till-covered prominence influences the saline deposits in any way is not known.

Individual deposits are of various shapes. In Canada, many of them are elongate and sinuous (fig. 1). Within the United

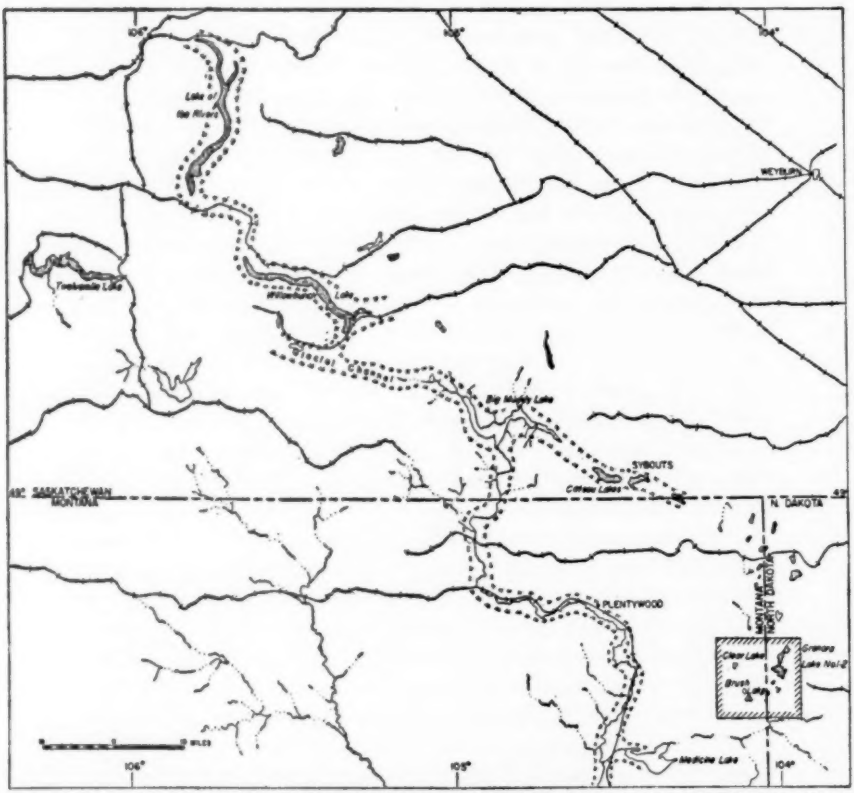


FIG. 1 — GENERALIZED MAP OF A SECTOR OF SOUTHERN SASKATCHEWAN, NORTHEASTERN MONTANA AND NORTHWESTERN NORTH DAKOTA SHOWING RELATIONSHIP OF LAKES TO GLACIAL CHANNELS
SODIUM SULFATE REPORTED FROM SHADED LAKES. FRESH-WATER LAKES ARE UNSHADED. SMALL BOXED-IN AREA IN LOWER RIGHT-HAND CORNER REPRESENTS LIMITS OF FIG. 2

States, however, only a few show such elongation. Numerous deposits are within broad valleys that can be traced for many miles. Lake of the Rivers and Willowbunch Lake in Saskatchewan are in such a broad valley (fig. 1). Both are saline (Cole 1926, map). The valley including these lakes can be traced southeastward to include Big Muddy Lake and the Coteau Lakes. Cole (1926, p. 122) states that the Coteau Lakes (i.e., Sybouts Lakes) are saline.

Similar sinuous patterns of deposits within valleys can be found in Montana and North Dakota. Here, however, they are not as clearly delineated as in Saskatchewan.

HYPOTHESES FOR LOCALIZATION OF SODIUM SULFATE DEPOSITS

This alignment of the saline deposits has been noted by both American and Canadian geologists. Alpha (undated, p. 7) has suggested that the northeastward alignment and localization of the deposits in this area (fig. 2) is along the preglacial courses of the Missouri and Yellowstone Rivers. In late Tertiary or early Pleistocene time these two streams may have flowed northeastward to Hudson's Bay (Alden, 1932, p. 58). Although this might explain the northeastward alignment of several American deposits, it cannot explain the Canadian deposits which lie far beyond the lateral limits of the Missouri River drainage.

Canadian authorities (Anonymous, 1947, p. 57) suggest that the alignment of the Saskatchewan deposits is along valleys cut during the withdrawal of the last ice, but later becoming stagnant reservoirs into which runoff waters charged with salines emptied. Concentration and deposition of the salts resulted from evaporation.

Although the saline deposits are associated with glacial channels, as suggested, I do not believe the Montana and North Dakota deposits are associated with the recessional-type channel described.

Tomkins (1948, p. 72) suggests that these deposits form where aquifers closely approach the surface and that the waters containing the salts accumulate in undrained basins, usually in sandy or gravelly areas. Cole (1926, pp. 121, 122), referring to the Coteau Lakes (fig. 1), indicates that the confining walls are of till. In eastern Montana and western North Dakota till not only walls the basins, but also underlies them.

A recessional channel would be floored with sand and gravel. Dagmar Channel (fig. 2) within this area is such an example, and contains no saline deposits. Actually, fresh-water lakes are present in such channels.

HYPOTHESIS OF PRESENT PAPER

Two types of channels are present in this area. One is floored with sand and gravel, and represents cutting during the withdrawal of the last ice. The surface of this type channel is till-free (fig. 3, stage C). The other type may have been formed at any time preceding or during the last advance of the ice, and was buried by that advance. It is till-surfaced. The till-surfaced swale in the south half of T. 34 N., R. 58 E. (fig. 2) is an example of this type of channel.

These buried channels in many places form discontinuous

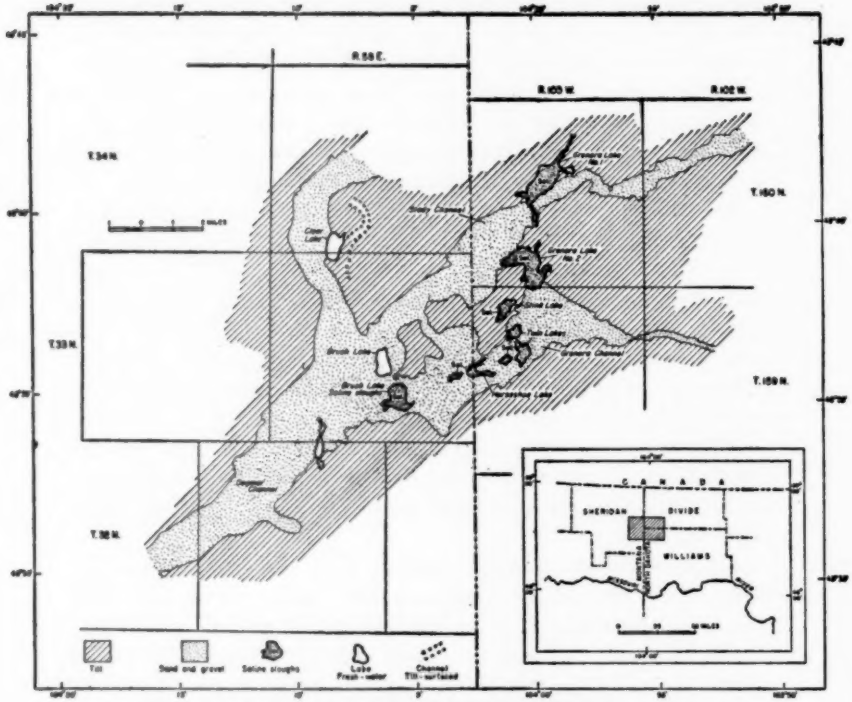


FIGURE 2 - GEOLOGIC SETTING OF SOME SODIUM SULFATE DEPOSITS IN NORTHEASTERN MONTANA AND NORTHWESTERN NORTH DAKOTA

THE LAKES MARKED "SAL" CONTAIN A BRINE HIGHLY CHARGED WITH SALINES. THEY MAY OVERLIE PERMANENT BEDS OF SODIUM SULFATE. DRILLING (LAVINE AND FEINSTEIN, UNDATED) INDICATES THAT GRENORA LAKES NOS. 1 AND 2 DO OVERLIE SUCH DEPOSITS. OTHER LAKES ARE FRESH WATER.

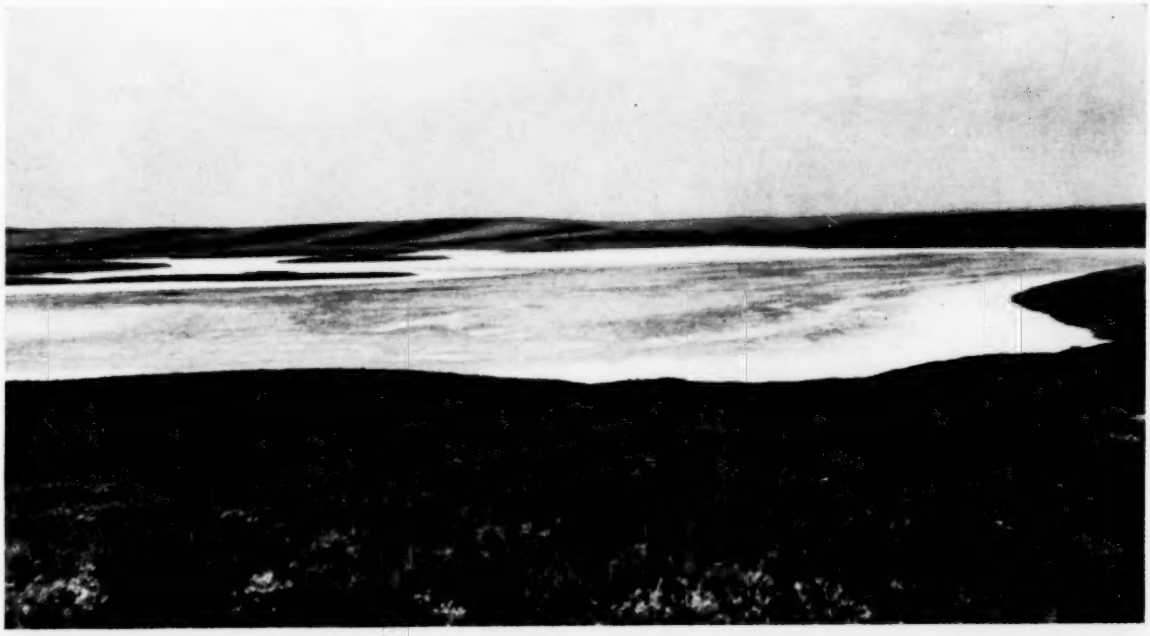
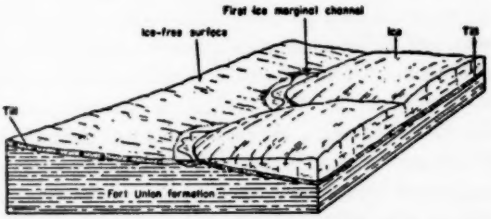
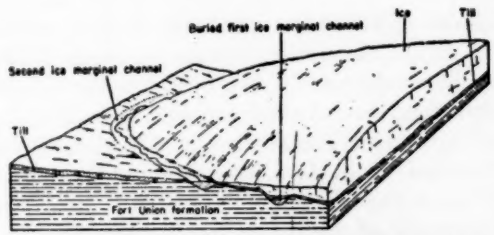


Plate 1. Typical sodium sulfate slough in northeastern Montana. White encrustation along the rim of the lake is part of the intermittent bed. Center of slough is occupied by saline-rich brine.

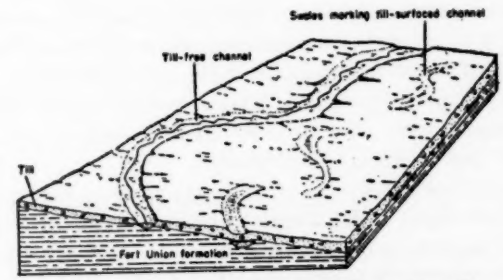
shallow, sinuous swales in the till-covered landscape. Apparently in some places the till forms a mere veneer, whereas in others it is thick enough to obliterate the former valleys completely. Undrained depressions are commonly within the floor of the swale.



Stage A.— A marginal channel is cut by outwash waters during a stillstand in the advance of a continental ice sheet.



Stage B.— A renewed advance of the ice buries the first marginal channel, and a subsequent stillstand results in a second marginal channel being formed beyond the first.



Stage C.— With subsequent melting of the ice, till-covered surface is exposed. The first marginal channel, which was over-ridden by the ice, now has its former course reflected by elongate undrained depressions whose bottoms are often occupied by small saline lakes. The second marginal channel, which was not buried by the ice, is till-free, and shows as a broad sand and gravel tract occupied by a small intermittent stream.

FIGURE 3 — THREE STAGES IN THE DEVELOPMENT OF TILL-SURFACED VALLEYS

Locally, a further complexity has masked the geological setting. During the withdrawal of the last ice, streams flowing southwestward away from the ice mantled many of the existing glacial features with sand and gravel. Thus, some of the till-surfaced channels were themselves thinly layered with sand and gravel, so that in places the till-free and till-surfaced channels superficially resemble one another. Stady and Grenora Channels (fig. 2) were formed by such distributary streams. Dagmar Channel was not. The sand and gravel veneer comprising the Stady and Grenora Channels mask a till-surfaced channel that is probably outlined by the string of sloughs consisting of Brush Lake Saline Slough, Horseshoe Lake, Twin Lakes, Stink Lake, and Grenora Lakes Nos. 1 and 2 (fig. 2).

It is suggested that the sodium sulfate deposits are here localized along the till-surfaced channels which were formed marginal to an ice front and later buried by a renewed ice advance (fig. 3).

The sodium sulfate lakes probably formed in undrained depressions within these till-surfaced channels. Their alignment, thus, is a reflection of the buried valleys. The ground water within these buried sand-and-gravel courses was under hydrostatic pressure. Wherever the till thinned, a spring probably reached the surface. Once the artesian waters broke through to the surface they were prevented from leaking out by the impervious till of the basin floor and sides. The waters that collected in these undrained basins were probably only slightly saline at first. With continued evaporation the salines were concentrated until saturation was reached, and an intermittent bed of crystals was deposited from the brine. Continued formation of these intermittent beds gave rise finally to the more massive permanent bed. Those springs within the center of the deposit were able to keep their passages free, as the permanent bed increased in thickness.

In a few places fresh-water lakes are close to saline sloughs. Examples are fresh-water Brush Lake and the saline slough due south of it known as the Brush Lake Saline Slough (T. 33 N., R. 58 E.) (fig. 2). I believe that these two different types of lakes result from the juxtaposition of a till-surfaced channel and a till-free channel. Within the till-free channel subsurface drainage permits flushing out of the salines, whereas in the till-surfaced channel the impermeable till prevents this. Grossman

(1949, p. 60), however, explains this phenomenon by a process of "basin integration." He notes that the saline sloughs, in several localities, are topographically lower than the adjacent fresh-water lakes. Thus, during periods of excessive rainfall the water rises in both lakes until the higher lake decants its salines into the lower. Hence, one lake will be fresh and the other saline. Insufficient data are available to test this hypothesis. It does not, however, affect the major premise presented in this paper.

CONCLUSION

Two types of glacial outwash channels are present in this part of the northern Great Plains. One type was formed during the withdrawal of the last ice and is filled with sand and gravel. Sodium sulfate deposits are not believed to form within this type of channel. The other type of channel has been buried by ice advances and now appears as a till-surfaced sinuous swale of relatively short length. Local depressions are within these swales. In certain of these depressions, the till was thin enough to permit the subsurface water flowing within the buried sand-and-gravel courses to break through to the surface. The weakly charged saline solutions, unable to escape through the impermeable till, were concentrated by evaporation until sodium sulfate crystals were deposited. In time, thick deposits accumulated. Hence, the major deposits of sodium sulfate are within depressions in the floor of this type of channel. The location and alignment of these deposits is controlled by the former course of the buried channel.

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DIFFERENTIAL THERMAL ANALYSIS OF CERTAIN IRON OXIDES AND OXIDE HYDRATES*

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ABSTRACT. Amorphous hydrated ferric oxides formed both by direct neutralization of ferric ion solutions and the oxidation of ferrous salts were thermally analyzed. The curves for both compounds, when fresh, show loss of adsorbed water followed by direct crystallization to hematite. By aging, goethite crystallizes from both these brown and yellow gels respectively. Its presence is indicated on the thermal curves.

$MgFe_2O_4$ and gamma-Fe_2O_3 can be distinguished by differential thermal analysis. The method also provides an easy way of detecting gamma-Fe_2O_3 in its mixtures with hematite.

Synthetic magnetite shows two exothermic peaks indicating its oxidation first to gamma-Fe_2O_3 which in turn transforms to hematite. Natural magnetite is oxidized directly, although very slowly, to hematite. Its thermal curve is characterized by a single flat exothermic "plateau" which starts at about 635°C. and does not end even at 1100°C. If samples with a wide particle size range are used, the curve may be modified by a small exothermic peak at 380-395°C. due to the recrystallization of the finer particles.

INTRODUCTION

DIFFERENTIAL thermal analysis consists of simultaneously heating the sample to be analyzed, along with another sample of inert material which does not undergo any thermal reaction in the temperature range investigated. The differential thermal analysis apparatus used in this study is not different from others described in the literature except for the removable sample block, made of "inconel" metal, which was designed by Professor J. W. Gruner and photographed by Manly (1950). The rate of heating was kept constant, at 13.5°C. per minute, giving a straight line relation between time and temperature in the interval between 100° and 1100°C. The specimen, unless otherwise indicated, was ground to pass 150 mesh screen, and then packed in its proper place in the sample block. A correspondingly fine grained alundum powder was used as the inert material. Whenever the sample consisted of an artificial mixture of different compounds, these were ground together in an agate mortar, and thoroughly mixed by rolling on a sheet of paper prior to their analysis.

* This study constitutes part of a thesis submitted by the writer to the graduate faculty of the University of Minnesota, in partial fulfillment of the requirements for the Ph.D. degree.

The substances used in this investigation include the following:

The brown gel.—$Fe_2O_3.nH_2O$, brown colloidal hydrated ferric oxide, prepared by the direct neutralization of a ferric salt solution with an alkali hydroxide.

The yellow gel.[1]—$Fe_2O_3.nH_2O$, yellow colloidal hydrated ferric oxide, prepared by the oxidation of freshly precipitated ferrous carbonate, usually with H_2O_2.

Natural magnetite.—Fe_3O_4, three samples of high purity from Mineville, New York, Kinney, Minnesota, and Kiruna, Sweden.

Synthetic magnetite.—Prepared by the reduction of various iron compounds as explained below.

Magnesium ferrite.—$MgFe_2O_4$, cubic ferromagnetic compound, similar in appearance and in x-ray powder pattern to gamma-Fe_2O_3 and might have been mistaken for it in the past.

Gamma ferric oxide.—Cubic ferromagnetic ferric oxide, prepared by the dehydration of synthetic lepidocrocite to constant weight in an open container at 280°C.

Synthetic lepidocrocite.—Gamma-$Fe_2O_3.H_2O$, obtained from the Minnesota Mining and Manufacturing Company (no. 2184), but not produced commercially. Its color corresponds to Ridgway's Ochraceous Orange, and it gives an excellent lepidocrocite x-ray pattern. Qualitative tests showed the presence of traces of ferrous iron which were quantitatively determined to be 0.15% FeO.

THERMAL BEHAVIOR OF THE BROWN AND YELLOW GELS

Through a combination of differential thermal analysis and x-ray powder photographs, several significant points were brought out which would have otherwise escaped notice. The changes that take place on aging[2] of either gel can be followed step by step by this method.

[1] Kulp and Trites (1951, p. 26) called this product also a brown gel. This is not the common practice.

[2] The process of aging includes the changes which take place spontaneously at room temperature, unless a different temperature is specified.

The Brown Gel

The first five curves (fig. 1) represent the thermal behavior of the brown gel at different stages of its aging process. Curves 1, 2 and 3 were made on the same sample, precipitated by adding excess 10N NH_4OH solution to a strong ferric chloride solution to pH 12. The dense precipitate was left overnight, then decanted and washed once with water. A sample was taken and used while slightly wet for the first determination (curve 1). The rest of the material was thoroughly washed with water and left wet at room temperature. The second determination was made on this wet material 3 days after its precipitation (curve 2). The third determination was made on the same material 46 days after its precipitation (curve 3).

Curve 1 shows a major endothermic reaction occupying the interval between 100°C. and 275°C. with the peak slightly below 200°C. This reaction is most probably due to the release of adsorbed water. It is followed almost immediately by a major exothermic reaction culminating in a sharp peak at 310°C. This reaction is caused by the crystallization of the amorphous anhydrous ferric oxide to hematite. Two x-ray powder photographs proved that the material was amorphous at 280°C., and consisted of hematite at 400°C.

Curve 2 shows an adsorbed water endothermic peak similar to curve 1. However, the exothermic peak due to the crystallization of amorphous Fe_2O_3 to alpha-Fe_2O_3 does not start until 400°C. It culminates in a peak, much broader than in curve 1, at 460°C. The composition of the material was proved by two x-ray powder photographs to be amorphous Fe_2O_3 and hematite at 300°C. and 550°C., respectively. This curve bears great resemblance to the one by Kulp and Trites (1951, fig. 9, curve 1, p. 42) made on material precipitated at pH 10, 25°C. and washed with dilute NH_4OH. Curiously enough, curve 1 (fig. 1) of the present study also shows a great similarity to Kulp and Trites' curve 2 (fig. 9, p. 42). The latter, however, was made on material precipitated at pH 5, 25°C. and thoroughly washed with water. In spite of the acidic solution and the thorough washing, the curve still presented a small endothermic kick around 400°C. indicative of ammonia, as was noticed by the authors. The important point is that Kulp and Trites obtained two curves on materials precipitated at two different pH values, while the author obtained two

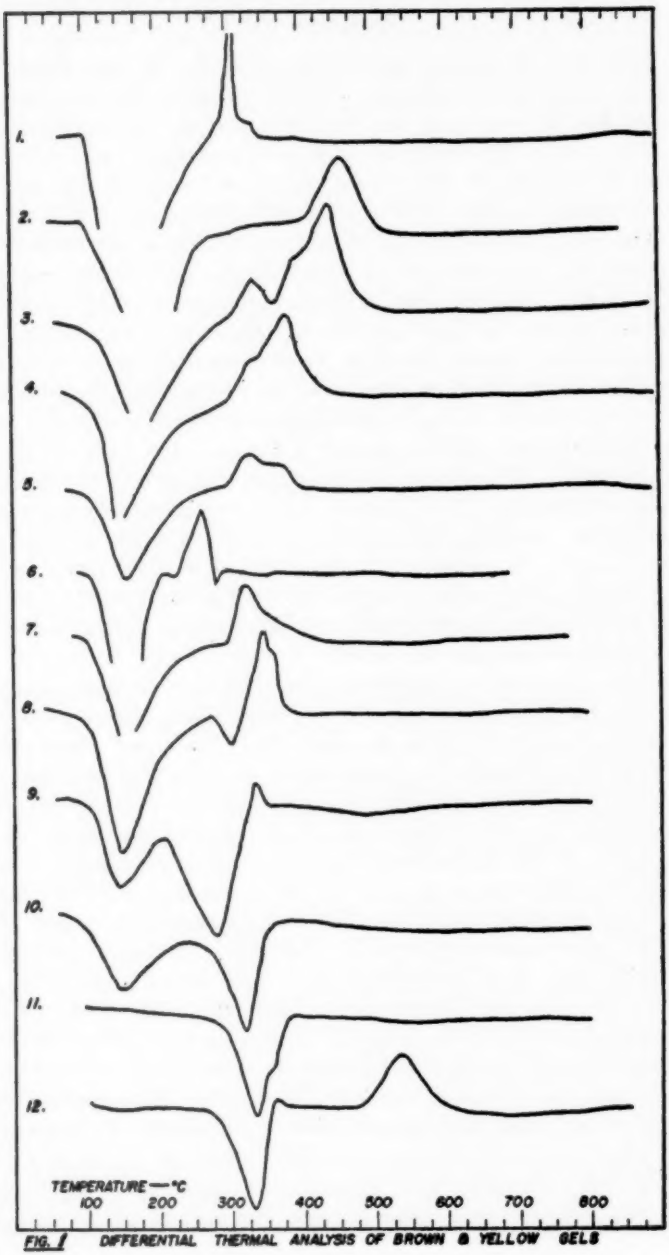

FIG. 1 DIFFERENTIAL THERMAL ANALYSIS OF BROWN & YELLOW GELS

curves similar to those of Kulp and Trites from the same sample before and after it was left to age at room temperature for 3 days. This fact suggests that the effect of the pH of the solution is possibly not as significant in the crystallization of goethite and hematite as has been assumed thus far.

Curve 3, unlike 1 and 2, was made with the sample uncovered, thus rendering the escape of water vapor much easier. An x-ray powder photograph taken of the sample just before the analysis showed a faint goethite pattern. The curve shows a strong endothermic reaction due to adsorbed water similar to those in curves 1 and 2. This is followed by a major exothermic reaction culminating in a peak at 440°C. and representing the crystallization of the amorphous Fe_2O_3 to hematite. This major exothermic peak is modified by an endothermic reaction due to the dehydration of the small amount of goethite present in this sample. The "endothermic" dent modifying the curve at about 365°C. represents the sum of the heat effects of the two simultaneous reactions: crystallization of the amorphous Fe_2O_3 and dehydration of goethite. X-ray powder photographs of this material heated to 290°C. and 500°C. showed faint goethite and good hematite patterns, respectively.

The small endothermic dent due to the dehydration of goethite does not show as well if the sample is covered, because the reaction and escape of water is spread over a longer period of time, thus giving a flattened dome which does not modify the exothermic peak as much. Curves 4 and 5 show the thermal record of two covered samples of aged brown gel. Curve 4 is that of an 18 months old brown gel which gave a fair goethite pattern before the analysis. The curve shows an adsorbed water, fairly strong endothermic peak at about 155°C. This is followed by the usual exothermic peak due to crystallization of the amorphous Fe_2O_3. This peak is but slightly modified by a steplike flattening around 330°C. due, it is believed, to the dehydration of the goethite which was present in the sample. This was proved by x-ray patterns of this material heated to 250°C. and 450°C. respectively.

Curve 5 represents the thermal behavior of a 28 months old brown gel. Its color was brownish red (more like hematite) but on x-raying it was found to show only goethite lines. Another x-ray photograph of this material heated to 250°C. showed no difference from the one at room temperature. The

curve shows an adsorbed water peak at 158°C. which is, however, much smaller in area and amplitude than in the previous cases. Loss of adsorbed water during aging is to be expected. The flattened dome or plateau occupying the interval between 300°C. and 385°C. represents the heat balance between the crystallization of amorphous Fe_2O_3 to hematite and the simultaneous dehydration of goethite, also to hematite. A significant point borne out by this analysis is the fact that even after 28 months of aging the material still retained a considerable amount of amorphous ferric oxide hydrate.

The Yellow Gel

The thermal behavior of the yellow gel is seen to be similar to that of the brown gel if one bears in mind the fact that its crystallization starts only a short period after its precipitation and usually proceeds at a faster rate. In the brown gel detectable crystallization never starts before several days and often a number of weeks after its precipitation, and proceeds very slowly. Another difference is that both the dehydration of goethite formed from the yellow gel and the crystallization of hematite from the amorphous material generally take place at a lower temperature than the corresponding reactions in the brown gel.

Curves 6, 7 and 8 were made on the same sample, formed by adding ammonium carbonate solution to a solution of ferrous chloride and oxidizing the precipitated ferrous carbonate with excess H_2O_2. The pH of the supernatant liquid was approximately 4.5. The dark yellow precipitate formed was left standing for one hour, decanted and washed once with water. A sample was taken and used while slightly wet for the first determination (curve 6) less than 2 hours after the precipitation of the gel. The rest of the material was thoroughly washed with water and left at room temperature. The second determination (curve 7) was made on slightly wet material 5 days after its precipitation. The third determination (curve 8), the only run in which the sample was not covered, was made on the same material 34 days later.

Curve 6 shows a major endothermic reaction covering the interval between 100°C. and 210°C. with the peak at approximately 185°C. This is followed by a rather sharp exothermic reaction culminating in a peak at 258°C. This reaction is

undoubtedly due to the crystallization of the amorphous material to hematite, a fact which was proved by two x-ray powder photographs of this material heated to 190°C. and 280°C., respectively. The small endothermic reaction following the major exothermic reaction is to be attributed to the presence of traces of an ammonium salt impurity. This is supported by the fact that the small endothermic reaction is absent from the following curves where the material was thoroughly washed before the analysis. An important point to be emphasized in connection with this curve is that the amorphous yellow ferric oxide hydrate goes directly to hematite with no indication of its crystallization to goethite as an intermediate step.

Curve 7 shows an endothermic reaction culminating in a peak at approximately 165°C., due to release of adsorbed water. The asymmetric exothermic peak covering the range between 297°C. and 415°C. with a peak temperature of 320°C. represents the net amount of heat produced when the crystallization of amorphous ferric oxide to hematite (exothermic) and the dehydration of goethite (endothermic) take place simultaneously. That a small amount of goethite was present in the sample was proved by an x-ray powder photograph of the yellow gel at room temperature which showed a very faint pattern of goethite.

Curve 8, made 34 days later and with the sample uncovered to facilitate the escape of water vapor, shows the usual adsorbed water endothermic reaction at 150°C. The dip in the curve, preceding the major exothermic peak, is to be attributed to the starting of the dehydration of goethite which was known to be present from a fairly good x-ray pattern taken at room temperature. The following exothermic reaction with the peak at 345°C. is of course due to the crystallization of the amorphous ferric oxide to hematite, while the dehydration of goethite is still proceeding. The small steplike flattening modifying the exothermic peak may also be due to the simultaneous dehydration of goethite.

It was noticed during the study of the colloidal ferric hydrates[3] that if $Na_2(CO_3)$ is used instead of $(NH_4)_2CO_3$ for precipitating the ferrous carbonate, a better crystallized goethite is obtained on oxidation and aging, provided other variables

[3]Gheith, M. A. (1951), Stability relations of ferric oxides and their hydrates; thesis submitted to University of Minnesota.

were kept constant.[4] The role played by sodium, however, is not satisfactorily understood. Curves 9 and 10 (fig. 1) represent the thermal behavior of yellow gel formed by adding a sodium carbonate solution to a ferrous chloride solution and oxidizing the precipitated ferrous carbonate with excess H_2O_2.

Curve 9, made with dry material, 9 days after its preparation shows a small endothermic peak at 145°C. representing the release of adsorbed water. This is followed by a major endothermic reaction with the peak temperature at 280°C. representing the dehydration of goethite. This reaction is probably interrupted or at least immediately followed by a rather small exothermic reaction with a peak at 330°C. due to the crystallization of the amorphous oxide to hematite. X-raying the starting material at room temperature gave a fairly good goethite pattern. The sample therefore must have consisted mainly of goethite and a small amount of amorphous hydrated ferric oxide.

Curve 10 represents a further stage in the aging of the yellow gel. The material, 23 months after its precipitation, consists only of goethite with some adsorbed water. The small adsorbed water peak lies at 150°C., while the goethite endothermic peak lies at 323°C.

Curve 11 shows the analysis of a 4½ year old sample which had been prepared by adding sodium carbonate solution to ferrous sulphate solution and oxidizing the product by blowing air through it for 2½ hours at 40°C. The yellow precipitate had given a good goethite x-ray pattern 2 days after its precipitation. The curve shows that this material represents the final stage in the aging process of the yellow gel. The only reaction present is the endothermic dehydration of goethite, culminating in a peak at 335°C.

Curve 12 represents the final stage of aging in another type of yellow gel, namely that precipitated under conditions favoring the crystallization of lepidocrocite rather than goethite. This particular sample had been prepared 4½ years earlier, by adding NaOH to a dilute $FeSO_4$ solution until pH 6, followed by blowing air through the solution for 2 hours. It had given a fairly good lepidocrocite x-ray pattern 2 days after its pre-

[4] Welo and Baudisch (1934) mention that a stabilizing effect of sodium was noticed by Hugget in connection with gamma-Fe_2O_3, formed by the oxidation of precipitated magnetite. Whenever NaOH was involved instead of NH_4OH during the preparation of gamma-Fe_2O_3, the product was stable at higher temperatures.

cipitation. Curve 12 shows the two familiar lepidocrocite reactions. An endothermic peak at 330°C. due to the dehydration of lepidocrocite to gamma-Fe_2O_3 is followed by an exothermic peak at 535°C., representing the phase transformation of gamma-Fe_2O_3 to alpha-Fe_2O_3. The curve shows only traces of adsorbed water.

Aging and Differential Thermal Analysis

Kulp and Trites (1951), noticing from the differential thermal analysis of a number of freshly prepared brown gels that they crystallize directly to hematite, concluded that in nature hematite is probably formed

> ". . . by the auto-dehydration of the hydrous ferric oxide gel which is a result of direct neutralization of a ferric ion solution. Goethite and lepidocrocite are not formed under these conditions but rather by the slow oxidation of certain ferrous compounds . . ."

The present study shows that on differential thermal analysis the fresh yellow gel, formed by the oxidation of certain ferrous compounds, behaves similarly to the fresh brown gel and crystallizes directly to hematite. Furthermore, the differential thermal analysis of aged gels indicates that in the laboratory goethite actually forms both from the direct neutralization of a ferric ion solution and the oxidation of certain ferrous compounds. There is no reason to believe that goethite does not form by the aging of the brown gel in nature.

The rather fast rate of heating generally used in differential thermal analysis in various laboratories (10 to 15°C./min.) seems to result in the dehydration of freshly prepared colloidal hydrated ferric oxide gels, whether yellow or brown, giving the amorphous anhydride Fe_2O_3, which crystallizes to hematite on further heating. Aging at room temperature, on the other hand, seems to fix part of the water present in the colloid more firmly to the solid framework, resulting in a definite hydrate of crystalline structure. Thus, this is another example following the hypothesis accepted by many chemists as to the effect of a spontaneous aging on some and probably all of the colloidal metal oxide hydrates.

THERMAL BEHAVIOR OF SYNTHETIC LEPIDOCROCITE AND GAMMA-FE_2O_3—HEMATITE MIXTURES

It was found that the thermal curve of synthetic lepidocrocite (curve 12, fig. 1, and curve 1, fig. 2) is identical with

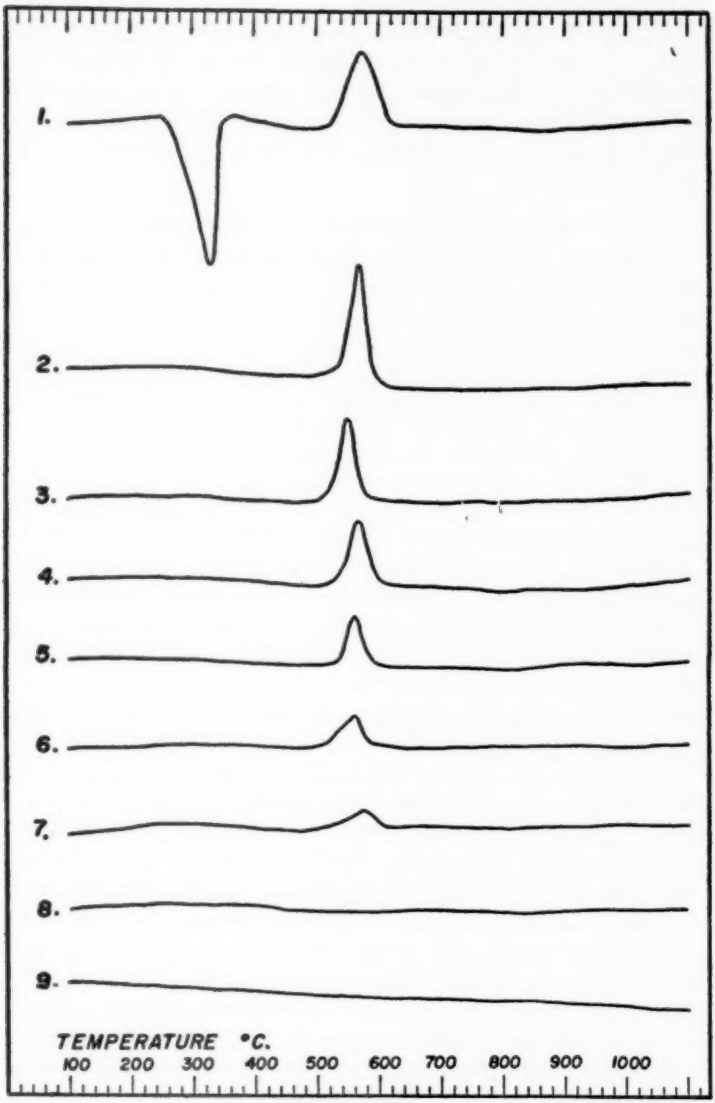

Fig. 2

1. Synthetic lepidocrocite
2. " " gamma Fe_2O_3
8. Hematite, Marquette Range, Mich.
9. Magnesium ferrite

3.	Hematite	20,	gamma–	Fe_2O_3	80
4.	"	"	33.3	"	"	66.7
5.	"	"	50	"	"	50
6.	"	"	66.7	"	"	33.3
7.	"	"	83.3	"	"	16.7

those of natural lepidocrocite except for the decidedly lower temperature at which the endothermic peak occurs. This may be attributed to the small size of the particles.

Curve 1 (fig. 2) representing the purest sample of those analyzed shows an endothermic peak at about 320° C. due to the dehydration of lepidocrocite to gamma-Fe_2O_3. This is about 30° C. lower than the corresponding peak of natural lepidocrocite thermal curve obtained by Kulp and Trites (1951, p. 43). Curve 1 also shows an exothermic peak at 568°C. representing the transition from gamma-Fe_2O_3 to alpha-Fe_2O_3. This peak temperature is about 100°C. or more higher than that of the corresponding reaction in natural lepidocrocite. In fact, all of Kulp and Trites' curves (1951, fig. 3) of natural lepidocrocite present this exothermic peak at or below 450°C. It is believed that the higher the temperature at which gamma-Fe_2O_3 is formed by the dehydration of lepidocrocite, the lower is the temperature of its transformation to hematite. Curve 2 of gamma-Fe_2O_3 shows one exothermic peak at about 570°C. representing its transformation to hematite. The sharpness of the peaks is an indication of the uniform particle size distribution.

In nature one may encounter some "hematite" samples which adhere to a hand magnet. The reason for magnetism in such cases is usually the presence of a small amount of ferrous iron, either as a constituent of intergrown magnetite or as a constituent of a solid solution (Sosman and Posnjak, 1925, p. 329). In the laboratory, however, and probably under rare conditions in nature, magnetism may be due to two additional causes, namely the presence of a ferromagnetic ferrite of a divalent element, or the presence of gamma-Fe_2O_3 in the "magnetic hematite." In view of this fact magnesium ferrite ($MgFe_2O_4$) was analyzed. Its thermal curve (no. 9, fig. 2) shows no reaction in the temperature range investigated. Curves 3 to 7 (fig. 2) represent the thermal behavior of artificial mixtures of gamma-Fe_2O_3 and natural hematite in known proportions. Because hematite produces no distinctive thermal peaks (curve 8), it therefore acts as an inert impurity, reducing the height of the gamma-Fe_2O_3 peak.

The temperature of the gamma-Fe_2O_3 peak is affected by the presence of hematite in a rather peculiar fashion. A mixture

Fig. 2. Differential thermal analysis of lepidocrocite, gamma-Fe_2O_3-hematite mixtures and $MgFe_2O_4$.

with 20% hematite produces the peak at the lowest temperature (550°C.), whereas a mixture with 83.33% hematite produces it at the highest temperature (576°C.). There is no regular increase in the peak temperature, however, by increasing amounts of hematite.

THERMAL BEHAVIOR OF SYNTHETIC AND NATURAL MAGNETITES

The behavior of magnetite on heating has been a controversial subject. Whether natural magnetite is oxidized by heating to gamma-Fe_2O_3 or directly to hematite has been argued back and forth by Sosman and Posnjak (1925), Wagner (1927), Welo and Baudisch (1925, 1934), Twenhofel (1927), Gruner (1926, 1927, 1930), Thewlis (1931), Verwey (1935), Goldzstaub (1935), Starke (1939) and others. Part of the confusion, at least, resulted from the difference in behavior upon heating between natural magnetite with a unit cell containing:

$$8Fe^{+++} \quad 8Fe^{+++} \quad 8Fe^{++} \quad 32\ O^{--}$$

and precipitated magnetites which according to Starke (1939) may have a lower ferrous iron content, sometimes as low as to correspond to a unit cell containing:

$$8Fe^{+++} \quad 8Fe^{+++} \quad 5\tfrac{1}{3}Fe^{++} \quad 26\tfrac{2}{3}\ O^{--} \quad 5\tfrac{1}{3}\ OH^{-}$$

As most of the discussion of this problem was based mainly on theoretical structural evidence, the present study was therefore undertaken to determine experimentally the differences in behavior between natural and synthetic magnetite. The curves obtained show that differential thermal analysis is particularly adaptable for such a problem. Unless otherwise mentioned the samples were not covered, so as to facilitate the oxidation of the ferrous iron.

Synthetic Magnetite

Synthetic magnetite gives two distinct exothermic peaks. The first peak corresponds to the oxidation of magnetite to gamma-Fe_2O_3 whereas the second corresponds to the change of gamma-Fe_2O_3 to hematite. Curves 1, 2 and 3 (fig. 3) are typical of the thermal behavior of dry synthetic magnetite in the absence of all traces of water vapor. The temperature at the first exothermic peak is 375°C., 320°C., and 280°C., whereas the second peak lies at 590°C., 620°C., and 650°C. in those three curves respectively. Comparison of these three curves confirms the

writer's previously mentioned belief that the higher the temperature of formation of gamma-Fe_2O_3, the lower the temperature of its change to hematite. This statement seems to be true for gamma-Fe_2O_3 prepared by either of its two general methods of preparation: the dehydration of lepidocrocite and the oxidation of synthetic magnetite.

Curve 4 shows the effect of adsorbed water on the thermal behavior of synthetic magnetite. The sample was prepared by the reduction at 190°C. in a sealed tube of gamma-Fe_2O_3 by camphor which was not previously dried. Camphor was later dissolved in benzene and this was followed by a magnetic separation under water to eliminate the hematite formed. The magnetite was left to dry for 2 days at room temperature before it was thermally analyzed. The sample was covered during the analysis, rendering the removal of H_2O rather sluggish. The curve shows an endothermic adsorbed water peak at about 110°C. The temperatures of the two exothermic peaks of synthetic magnetite are lowered considerably. The catalytic effect of water vapor on the transformation of gamma-Fe_2O_3 to hematite is obviously indicated from the fact that although gamma-Fe_2O_3 formed around 210°C., it was transformed to hematite at the comparatively low temperature of 460°C., more than 130°C. lower than when moisture is completely absent.

Natural Magnetite

Curves 5, 6, 7, 8, 9 and 10 (fig. 3) are typical of pure natural magnetite. The main and striking feature of the curve is the extremely flat exothermic "peak" denoting the oxidation of the ferrous iron. The reaction starts between 625°C. and 650°C., culminates roughly at 1000°C. and does not end even at 1100°C. X-ray powder diagrams of the products of differential thermal analyses showed the presence of both magnetite and hematite. The color of the products was reddish black, and the presence of magnetite was further confirmed by quantitative oxidimetric determination of the ferrous iron content. From 3.26 to 4.12% FeO was found to remain in the material after it was heated to about 1100°C. This means that 10.52 to 13.29% of the original magnetite had not yet been oxidized. All this points to the stability and difficulty of oxidation of Fe_3O_4 magnetite in nature in the absence of water vapor and/or catalysts.[5]

[5] Gruner (1930) noticed that magnetite starts to oxidize to hematite in the presence of steam at 258°C. The reaction is catalyzed by traces of HCl.

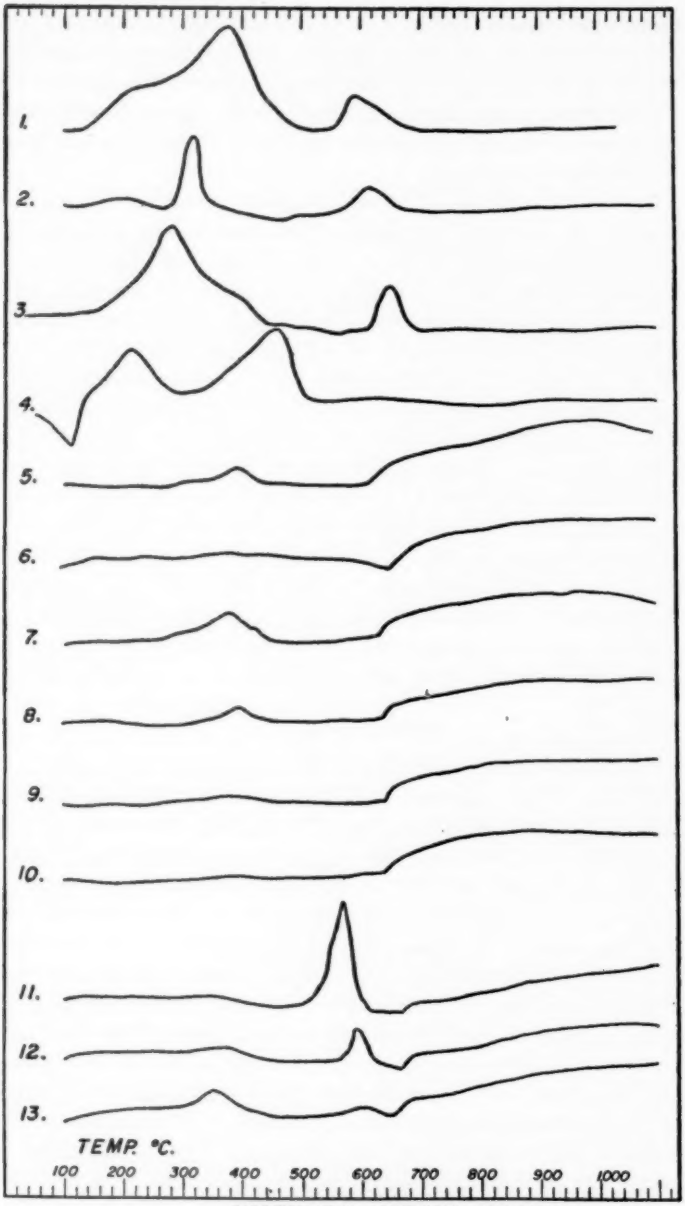

FIG. 3 DIFFERENTIAL THERMAL ANALYSIS OF MAGNETITES.

The second feature of the thermal curve of natural magnetite is the small exothermic peak whose temperature ranges from 380°C. to 395°C. This peak, which shows better on curves 5, 7 and 8 (fig. 3) is rather problematic. It cannot be attributed to an impurity inasmuch as the possibility of the presence of the same type of impurity in magnetites from such varied localities and with different geneses is rather meager. Besides a careful magnetic separation under water under the binocular microscope was carried out before the samples were thermally analyzed. The possibility of the presence of some maghemite as an oxidation product in the original magnetite is negligible as the small exothermic peak occurs at a temperature much lower than that of the phase transformation of gamma-Fe_2O_3 to hematite in the absence of water vapor. Microscopic examination of the samples indicated the absence of oxidation products. Furthermore, artificial mixtures of natural magnetite and synthetic gamma-Fe_2O_3 in various ratios were thermally analyzed and the results are shown in curves 11, 12 and 13 (fig. 3). The effect of "dilution" is indicated by the lower amplitudes of

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Fig. 3. Differential thermal analysis of magnetites.
(Samples 1 to 7 were X-rayed prior to their analysis.)

1. Synthetic magnetite: formed by the reduction of artificial goethite with a large amount of oxalic acid at dull red heat in open tube.
2. Synthetic magnetite: formed by the reduction of hematite with a large amount of oxalic acid at dull red heat in open tube.
3. Synthetic magnetite: formed by the reduction of gamma-Fe_2O_3 with dried ethyl acetate at 190°C. in sealed tube.
4. Synthetic magnetite: formed by the reduction of gamma-Fe_2O_3 with camphor at 190°C. in sealed tube.
5. Natural magnetite crystals: Kinney, Minnesota; pure, with only 0.05% excess of Fe_2O_3; finely powdered to pass 150 mesh screen.
6. Natural magnetite: Mineville, New York; portion of a single coarse crystal. University of Minnesota No. B380; size: —35 + 60 mesh.
7. Natural magnetite: Kiruna, Sweden; very finely crystalline, powdered to pass 150 mesh screen.
8. Natural magnetite: the same as used in curve 7; powdered to pass 60 mesh screen.
9. Natural magnetite: the same as used in curve 7; size: —60 + 100 mesh.
10. Natural magnetite: the same as used in curve 7; size: —20 + 35 mesh.
11. Artificial mixture of natural magnetite (Kiruna) and gamma-Fe_2O_3 (from dehydration of lepidocrocite at 280°C. for 4 days) 1:1; size: —150 mesh.
12. Mixture of the same materials as in curve 11, but the ratio is 5:1; size: —150 mesh.
13. Mixture of the same materials as in curve 11, but the ratio is 15:1; size: —150 mesh.

the peaks. Examination of these three curves shows that a calibration curve can be drawn by plotting the area under the peak of the gamma-Fe_2O_3 to hematite phase transformation against the concentration of either gamma-Fe_2O_3 or magnetite. Therefore, whenever the claim is made that a crystal of magnetite was partly oxidized to maghemite, a differential thermal analysis curve might be of great use in settling the question by correctly identifying the products.

A third possibility is the oxidation of the magnetite to gamma-Fe_2O_3. This possibility is immediately eliminated after seeing the thermal behavior of the material at higher temperatures and noting that the final product still contains magnetite. Microscopic examination of the magnetite samples before and after this reaction of the first peak took place showed no difference except for the very slightly more blue color of the sample.

The only explanation that might account for this small exothermic peak is the recrystallization of the extremely fine magnetite particles present in the sample. Recrystallization in a monomineralic system reduces the total amount of free energy in the system which thus attains increased physical stability. Such a process will result in an exothermic peak, the area of which is proportional to the amount of energy released. The extent to which such recrystallization progresses is governed by the main forces which promote the recrystallization. In the present case those forces are the range in grain size within the sample and the mobility of the substance in the intergranular film (a function of temperature).

The fact that such a recrystallization occurs in magnetite and not in most other minerals might be at least partially explained by the high "force of crystallization" of magnetite, or to use Eskola's terminology, its high "form energy." In his crystalloblastic series Becke, arranging metamorphic minerals in order of decreasing "force of crystallization," places magnetite almost at the top of the list, preceded only by sphene and rutile.[6]

The next logical step to determine whether this small exothermic peak was due to recrystallization of the fine particles or not, was to thermally analyze magnetite samples with carefully controlled particle sizes and mixtures thereof. The results of such investigation are shown in figure 3, curves 6, 8, 9, and

[6] For further discussion of the "force of crystallization" see Turner, 1948, pp. 154-158.

10. It is seen that the height of this exothermic peak decreases with decreasing amounts of fine particles in the sample until it almost completely disappears when comparatively coarse material of a narrow particle size range is used (curves 6 and 10).

In this connection it is significant to mention two general observations made by workers in the field of differential thermal analysis. The first is by Spiel et al. (1945), concerning the effect of particle size on the thermal analysis curves of kaolinite. They found that the areas of the peaks (except for the adsorbed water peak) decreased appreciably with decreasing particle size (except for the interval between 5 to 20 and 1 to 5 micron fractions). The second observation is by Kerr et al. (1949), to the effect that a narrow range of particle size results in a much sharper peak than does a wide range. As the preceding one, this observation was made in connection with the clay minerals. In the present investigation it is seen that the small exothermic peak of magnetite behaves diametrically opposite to the above two observations: the finer the particle size the larger the area of the peak; and the narrower the particle size range the flatter and less sharp is the peak (curves 6, 7, 8, 9, and 10, fig. 3). This indicates that we are dealing here with a different type of reaction than those investigated by Spiel and by Kerr. This negative approach also favors the idea of explaining this small exothermic peak by the recrystallization of the fine particles.

To recapitulate, differential thermal analysis shows experimentally that when natural magnetite (Fe_3O_4) is heated it is oxidized directly to hematite. Gamma-Fe_2O_3 does not form as an intermediate step, in contradistinction to the oxidation of most synthetic magnetites. This is in harmony with theoretical evidence presented by Gruner (1927), Verwey (1935) and others, based mainly on the crystal structure of both magnetite and gamma-Fe_2O_3. The oxidation of magnetite in dry air is a rather difficult and extremely slow process which starts to proceed at a noticeable rate only above 620°C. Fine grained magnetite may undergo slight recrystallization to form coarser grains before this temperature is reached.

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Radiologic Physics, 2d ed.; by CHARLES WEYL and S. REID WARREN, JR. Pp. xix, 491; numerous figs. Springfield, Illinois, 1951 (Charles C. Thomas, $10.50).—This book is an introduction to physics for the radiologist. Over half the material consists of electricity, x-rays, atomic and nuclear physics. The remainder of the work is devoted to the physical aspects of x-ray therapy and roentgenographic techniques. It is obvious that intelligent use of physical tools can best be made by people with a fundamental understanding of the basis of the techniques. It is also true that significant research advances will be made primarily by workers who have this fundamental knowledge. The authors of *Radiologic Physics* have attempted to supply the physical bases of radiology to students with a negligible background in physics and mathematics.

In the construction of a book such as this a fine balance must be obtained between theory and experiment. The authors have done this, but only at the expense of making theory look like a collection of unrelated facts. There is no underlying guiding train of thought which ties atomic physics into a compact whole. I should think that some qualitative wave-mechanics would be more useful and interesting than a section on transformers, motors, and distribution systems. The effort to condense the material has led to strange results in some cases. For example, on page 131 is the implication that Avogadro's number represents only the number of molecules in a mole of an *ideal* gas. The number of other errors is small (kenotron is misspelled, however). *Radiologic Physics* confirms my belief in the principle that there should be no courses such as English for physicists or Physics for radiologists. I would venture to reassure the authors that future changes in the values of physical constants will have a negligible effect on radiology.

R. B. SETLOW

Mathematical Engineering Analysis; by RUFUS OLDENBURGER. Pp. xiv, 426; 220 figs. New York, 1950 (The Macmillan Co., $6.00).—It is well known that a "good background in mathematics or engineering or both does not insure that the research engineer will have a facility for making the transition from the physical engineering situation to the corresponding mathematics." Because of the sad truth of this fact, this book was written to make that transition easier, and such an aim has been achieved with a large degree of success. As such, the present work is addressed to research directors in industry, to engineering analysts, to developmental engineers, and to applied scientists in various fields, as well as to students of engineering analysis and industrial physics.

The basic laws of engineering, and the theoretical physics involved in these laws, are developed from a minimum number of

assumptions, so that the reader may obtain a logical, physical, and mathematical picture of the fundamental concepts of engineering in common use. It is obvious that in attaining or attempting to attain this goal, a wide number of separate fields must be encompassed. Therefore, under the all-embracing categories of The Mechanics of Rigid Bodies, Electricity and Magnetism, Heat, Elasticity, and Fluid Mechanics, we are presented with an embarrassment of riches in the types of examples covered.

There is no intention in *Mathematical Engineering Analysis* of reviewing in detail the fore-mentioned subjects from an undergraduate viewpoint. Rather, there is plentiful application of the concisely demonstrated basic laws to as many problems as space will allow. In addition, significant problems are left to the reader, with the answers and hints to answering contained in the last portion of the book. Reference is made throughout to standard works in the field.

The sections on Heat and Elasticity are particularly noteworthy, and deserve high praise for their clarity of expression in basic theory as well as the manner in which simplifying assumptions are made in the illustrated problems. The motivation for the assumptions is always clear in these portions.

The only criticism that might be leveled against the present work lies in the fact that some problems were treated in somewhat too sketchy a manner but, since this is a rare occurrence, the criticism is a minor one. N. STONE

World Geography of Petroleum; edited by Wallace E. Pratt and Dorothy Good. Pp. 464; 98 photographs; 60 figs. Princeton, N. J., 1950 (Princeton University Press, $7.50).—"The distribution and nature of the accumulations of petroleum in the crust of the earth are two prime subject matters of this book. It also portrays the character of the industry that has discovered and developed these mineral fuels . . . ; and it considers the impact of petroleum and the petroleum industry on our social and industrial economies." This quotation from "A Geologist's Foreword" by Wallace E. Pratt sets the stage for the 23 chapters, divided into four parts, as follows:

Part I (pp. 1-24), "Petroleum in the Ground," is a very fine condensation of geological principles, exploration for petroleum, and estimation of reserves by the late Eugene Stebinger.

Part II (pp. 25-42), "The Functional Organization of the Petroleum Industry," is an effort by W. B. Heroy to lay further groundwork for an understanding of the petroleum industry by discoursing on development and production, storage, transportation, refining, and distribution. This is obviously a very large order in the space used.

Part III (pp. 43-330) is the "meat" of the book. It is a description of the world petroleum regions, divided into 16 areas, discussed by the world's leading authorities on petroleum geology and production, among the best known of whom are A. I. Levorsen, G. M. Lees, and D. Dale Condit, in addition to Pratt and Stebinger who appeared earlier in the book. Nowhere in print, to this reviewer's knowledge, is there any comparable combination of historical, geological, and other useful facts about the world oil areas. This part of the book alone makes it a necessity in every library, private or public. It can be read with full understanding, not only by all who work in petroleum, but also by any educated person outside the industry.

Part IV (pp. 331-392) examines the "Aspects of Utilization." In the chapter "The Availability of Petroleum," Kirtley F. Mather leaves something to be desired in his coverage of the subject and his conclusions. This may be due in part to the fact that the latest figures available to him were 1948. No doubt one who had spent his working life in petroleum geology or production could have given a more realistic appraisal and accurate forecast of this important subject. This is followed by "Geographical Aspects of Petroleum Use in World War II" by the Office of the Army-Navy Petroleum Board; "World Patterns of Civilian Utilization" by John W. Frey; "A Statistical Survey" by Anastasia V. Burkalow; and "The Effect of the World Distribution of Petroleum on the Power and Policy of Nations" by Herbert Feis. This last chapter will be recognized by every student of world politics as a subject of prime interest today, about which many volumes could be written.

The quality of the writing throughout is good. The book is extensively and intelligently illustrated with 60 maps and diagrams, 46 of which were expressly prepared for this publication, and with nearly 100 well chosen photographs. The usefulness of the book is greatly enhanced by the selected bibliography which is arranged in the same topical order as the book, and also by an exhaustive index.

This book is in every way a worthy addition to our fund of knowledge of the petroleum industry and the areas in the world which contribute the magical, modern mineral fuel to our civilization.

A. RODGER DENISON

Der Zeitfaktor in Geologie und Paläontologie; by Otto H. Schindewolf. Pp. 114; figs. 18. Stuttgart, 1950 (Schweitzerbart). —This booklet is an expanded version of Schindewolf's inaugural lecture on assuming the professorship of geology and paleontology at the University of Tübingen in 1948. It might be considered an elaborate footnote to his monumental "Grundfragen der Paläontologie," issued by the same publisher at about the same time. There

is some duplication, but the present smaller work includes interesting additional details, particularly some new data on survivorship and evolutionary rate distributions in gastropods, Foraminifera, and brachiopods. Other sections emphasize the inferences that evolution is more rapid in the origin of major groups than it is thereafter and that evolution is a periodic process but without evident correlation with periodic earth events such as mountain building. Such data and discussions have a usefulness apart from reference to Schindewolf's theory of saltatory evolution ("typostrophism"). That theory, with which this reviewer disagrees, is fully expounded in the larger book and is taken rather for granted in this booklet. It therefore need not be discussed in this review, but two protests may be placed on record. Sewall Wright is quoted (p. 81) out of context as if he agreed with the theory of "typostrophism," which really is strongly inconsistent with the whole body of Wright's work. Dietrich is quoted (pp. 72-73) to the effect that there is no intermediate form and no gradual transition between *Parahippus* and *Merychippus*, which correctly represents Dietrich's statement but which is flatly false as to the facts. G. G. SIMPSON

Das Klima der Vorzeit; by MARTIN SCHWARZBACH. Pp. viii, 212; 70 figs. Stuttgart, 1950 (Ferdinand Enke, 19 German marks unbound, 21.80 bound).—This slight-appearing book is an able and critical summary of the evidence, the knowledge, and the speculations of geologists and meteorologists on the past climates of the Earth. Naturally the glacial climates of the Pleistocene come in for the lion's share of attention, in all these aspects, but Schwarzbach has also brought together what information he could find on earlier climates.

After a short but very interesting historical review (complete with verse quotations) and a shorter discussion of significant facts about present climate, the author discusses thoroughly and critically the geological criteria for such climatological elements as temperature, precipitation, and wind, and for seasonal and other variations. There follows a summary of the climatic evidence period by period; this part of the book seems less rewarding than the first part. Partly this is because evidence for pre-Cenozoic climates (except glacial periods) is very meager, for which the author can hardly be blamed, but also it is a little disappointing to find all redbeds cited indiscriminately as evidence of dry climates and to be told again that continental ice-sheets necessarily foster permanent anticyclones. After this, there is a short but pithy discussion of theories explaining climatic changes (again principally glaciation), from which Schwarzbach concludes that such changes are extremely complex phenomena depending on many factors, of which the most important appear to be changing patterns of highland, lowland,

and sea, and changing intensity of radiation from the sun. In a final section on future climates, Schwarzbach cites both optimistic and pessimistic predictions (wine-vineyards in north Germany vs. a new ice sheet) and wittily concludes that, faced with these contradictory opinions, one may well prefer to wait it out. A bibliography of more than 800 titles testifies to the author's diligence, but unhappily journal articles are cited only by periodical, volume number, and year; the omission of title and pagination will prove vexing.

The book is not intended for popular consumption but for professional scientists; as the author says, the exposition is "lehrbuch- und handbuchmässig." Nevertheless, if a foreigner may presume to offer an opinion on style, the writing is clear, lively, and entertaining, reflecting a man of ability, humor, and broad intellectual interests. Not least worthy of mention are the quotations in German, English, and French at the heads of many of the sections, mixing Goethe, Herder, and the Bible with Lyell, Walther, and Daly. The book merits wide attention as a summary of what is known of past climates and as a guide to problems for future work.

JOHN RODGERS

The Nature of Natural History; by MARSTON BATES. Pp. 309. New York, 1950 (Charles Scribner's Sons, $3.50).—Dr. Bates' book gives the reviewer the feeling that there are two rather different pieces without a comfortable transition between them. The first fifteen chapters are for the layman without biological training, and Bates has set out to provide a substitute for that training by summarizing in simple language the most advanced state of knowledge of each field related to natural history. This pedagogic section describes plainly the present state of knowledge of the classification, geological history, reproduction and development, environment, interrelationships, behavior, and evolution of animals and plants in natural conditions.

The final three chapters deal with: the application of science for the human economy; "The Natural History of Naturalists"; and the essence of the scientific method. In these Bates sets forth his own philosophy, purposes, and hopes. This caudal portion, at least, is as interesting for scientists as for laymen.

Dr. Bates, long with the Rockefeller Foundation, is an authority on mosquito biology. His respected research in this field has been concentrated in Colombia, Albania, and Egypt. He has been particularly interested in tropical natural history, and he has drawn fully from his own field experiences in all parts of this book. His definitions are admirably clear, for example his non-technical definition of the species on page 14.

Unaccountably, there are no illustrations. It is difficult to justify,

in a book whose aim is to explain simply a patently complex subject, anything less than a wealth of figures and diagrams. Not only does the text remain needlessly obscure, but very many potential readers are not likely to try the book at all.

Errors are remarkably rare, but anthropomorphic phrasing recurs uncomfortably often. For example, on page 26 one reads: "All parasites become, through the eons of geological time, increasingly lazy as they discover how easy it is to make their hosts do all of the work."

Bates calls for the reconciliation of science and philosophy. His own words are (p. 283): "The difference between science and philosophy, as I see it, is a matter of method. The one seeks for conceptual schemes through the methods of controlled observation and experimentation, while the other arrives at its concepts through introspection, . . . and the goal, of understanding, of developing a correspondence between the external world of reality and the internal world of the mind, is surely identical." This seems to me too blithe a reconciliation. With few exceptions, biologists seem to be materialists who regard virtually all the living phenomena, including thinking, as ultimately explainable through biological investigation. To the degree that they consider "through introspection" causes apart from the material, they leave science for philosophy or perhaps religion. CHARLES L. REMINGTON

Water in the Physiology of Plants; by A. S. CRAFTS, H. B. CURRIER, and C. R. STOCKING. Pp. xxi, 240; 56 figs, 49 tables. Waltham, Mass., and New York, 1949 (The Chronica Botanica Co., and Stechert-Hafner, Inc., $6.00).—It is quite remarkable that after a lapse of about 20 years during which no monograph on water relations in plants appeared, two should be published only a few months apart—the book under review and one by Paul Kramer called "Plant and Soil Water Relationships." Fortunately, there is very little overlap between the two books, and they supplement one another very well indeed.

Owing to wartime difficulties, the book by Crafts, *et al.*, was very much delayed in publication. By use of brief notes in the preface the authors have been able, however, to add pertinent and significant information which appeared after the book went to press.

The approach used is to a large extent that of the plant physiologist with a strong leaning toward physical chemistry. A liberal amount of original work by the authors is reported and an attempt has been made to synthesize new concepts from the published literature.

As a means of orienting the reader, source material of major caliber has been classified and arranged in the introductory chapter according to the branch of water relations covered. This should

prove quite useful to those wishing to enlarge their background in a given phase of the subject. In Chapter II the structure of water is considered in great detail. The numerous theories advanced since 1900 to account for the peculiar characteristics of water are reviewed, and the present state of knowledge on this point is given. This serves as an introduction to the chapter on the "Properties of Solutions," and helps in preparing one for the chapters on "Osmosis and Osmotic Pressure" and "The Mechanism of Osmosis." In these and later chapters the terminology agreed upon by the Committee on Water Relations of the American Society of Plant Physiologists has been employed. This should be helpful to those who have been confused by the multiplicity of synonyms encountered in the field of water relations. "Intracellular Distribution" is considered in very interesting fashion, and is followed by "Osmotic Quantities of Plant Cells" where points of method and technique are described in scholarly detail.

Despite all efforts to account for water uptake on purely physical grounds, the equations still lack one or more factors. This fact is considered in the chapter on "Active Cell Water Relations" where evidence is weighed that a goodly amount of water may be transported or retained against an apparent diffusion pressure gradient, by processes requiring the expenditure of metabolic energy. Following in logical sequence are chapters on "Uptake and Movement of Water in Plants" and "Water Loss and Water Retention," closing the book. These sections are devoted to a consideration of techniques and knowledge available from a wide variety of researches on the transport of material within plants possessing a vascular system. A critical theoretical discussion at this point would have helped greatly in unifying some of the information given. This gap has since been filled in a critical review article by Crafts in *Botanical Review*.

Clear and crisp summaries are used at the end of each chapter. These are of exceptional value to the reader who wishes to learn the contents of a chapter quickly. Another great help which everyone using the book will appreciate is the 17-page bibliography together with the excellent author and subject indices. It is to be anticipated that all with a general interest in plant physiology, as well as specialists in water relations, will use and appreciate this monograph.

The usual high standards of the Chronica Botanica Press are again in evidence. Binding, typography, design of the page, choice and use of sketches for the end papers all show purpose, good taste, and pride in workmanship.

AUBREY W. NAYLOR

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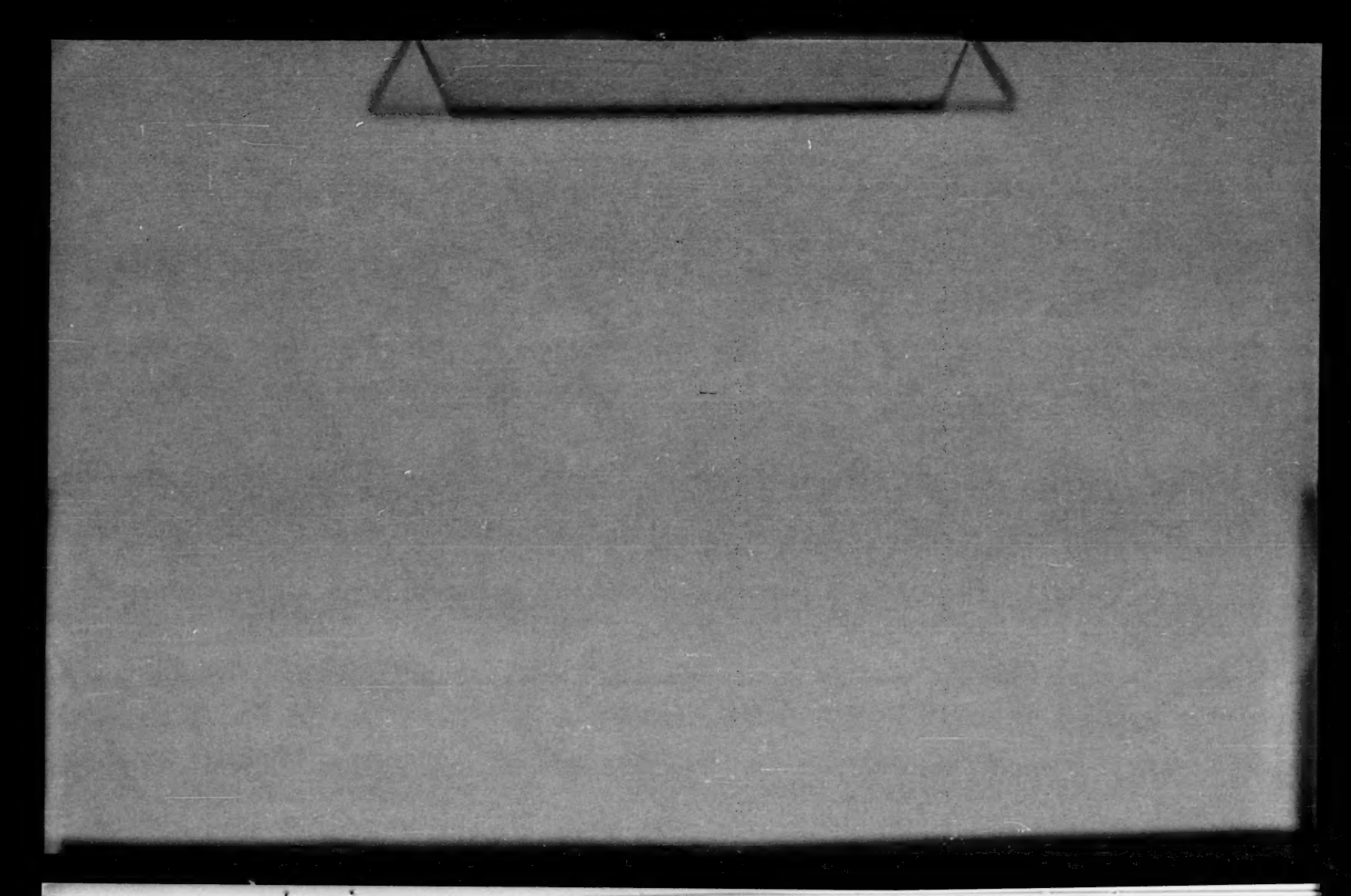
ERRATUM

In Carleton A. Chapman's article "A New Quantitative Method of Topographic Analysis," Volume 250, June, 1952, the formula on page 436 should read:

$$r = \sqrt{2}\, R \sin \frac{a}{2}.$$



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